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THE DEVELOPMENT AND APPLICATION OF EQUIPMENT
FOR THE STUDY OF ORAL - PHARYNGEAL
NEUROMUSCULAR BEHAVIOUR.

BY

RICHARD EDMUND ELLIS.

A thesis submitted for the Degree of Master of Philosophy
in Physics at the Open University.

1978

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SUMMARY.

While developing new techniques for the treatment of incompetence of the soft palate, which gives rise to hypernasal speech, it became obvious that equipments were needed to help to assess the degree of nasal escape of air with speech and to attempt to make the earliest possible diagnosis of incompetence. The latter being important if vital, early schooling is not to be missed.

Two such equipments are the subject of this work. The first, the Exeter Nasal Anemometry System, is in full clinical use in the Devon Health Area and in some special units in other Health Authorities. A description is given of the use of a heated thermistor anemometer, mounted in a nose-mask, together with its associated electronics to produce permanent chart records of correlated speech and airflow patterns. These charts are used by therapists both to assess and to monitor improvement of hypernasal speech.

The second apparatus, although not yet in full clinical use, has been used to collect data on the sucking, swallowing and respiration patterns produced by neonates during feeding. It is hoped that any malfunction of the musculature involved, which may later lead to speech defects, will show as anomalies in this data, when compared to that established for normal infants.

The development of these equipments is described, the problems involved in their use in a clinical situation and the production of suitable data are discussed. Examples of typical charts are shown and further discussion is given on the use of the data by a clinician.

The Exeter Nasal Anemometer is the subject of a British Patent application by the University of Exeter. A paper on its use has been submitted for publication.

ELLIS, R.E. et al. (1978)

A system for the assessment of nasal escape during speech.
Brit. J. Disorders of Communication.

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It is with sincere gratitude that I acknowledge the help and encouragement given to me during this research project.

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I wish to express my thanks to Mr.W.G.Selley who, as clinical supervisor, has worked many hours to make this study possible.

I would like to thank Professor G.N.Fowler and the late Professor G.K.T.Conn for allowing me access to the facilities of the Department of Physics at the University of Exeter, also Dr. F.S.Brimblecombe for allowing the clinical measurements to be made in the Special Care Baby Unit of the Royal Devon and Exeter Hospital.

Many thanks go to Nursing Officer Miss Jean Boxall, her staff and Mrs. Joan Turner for their help in the making of so many recordings and charts.

I am grateful to the Regional Hospital Board and to the National Fund for Research into Crippling Diseases for their financial support, without which the work could not have been performed.

I wish to thank the Open University and particularly Professor G.F.Elliot for the opportunity to conduct this research and present a thesis for the degree of Master of Philosophy.

This thesis is dedicated to my wife Andrea and my sons Richard and Steven. I owe them so much that it is impossible to express it.

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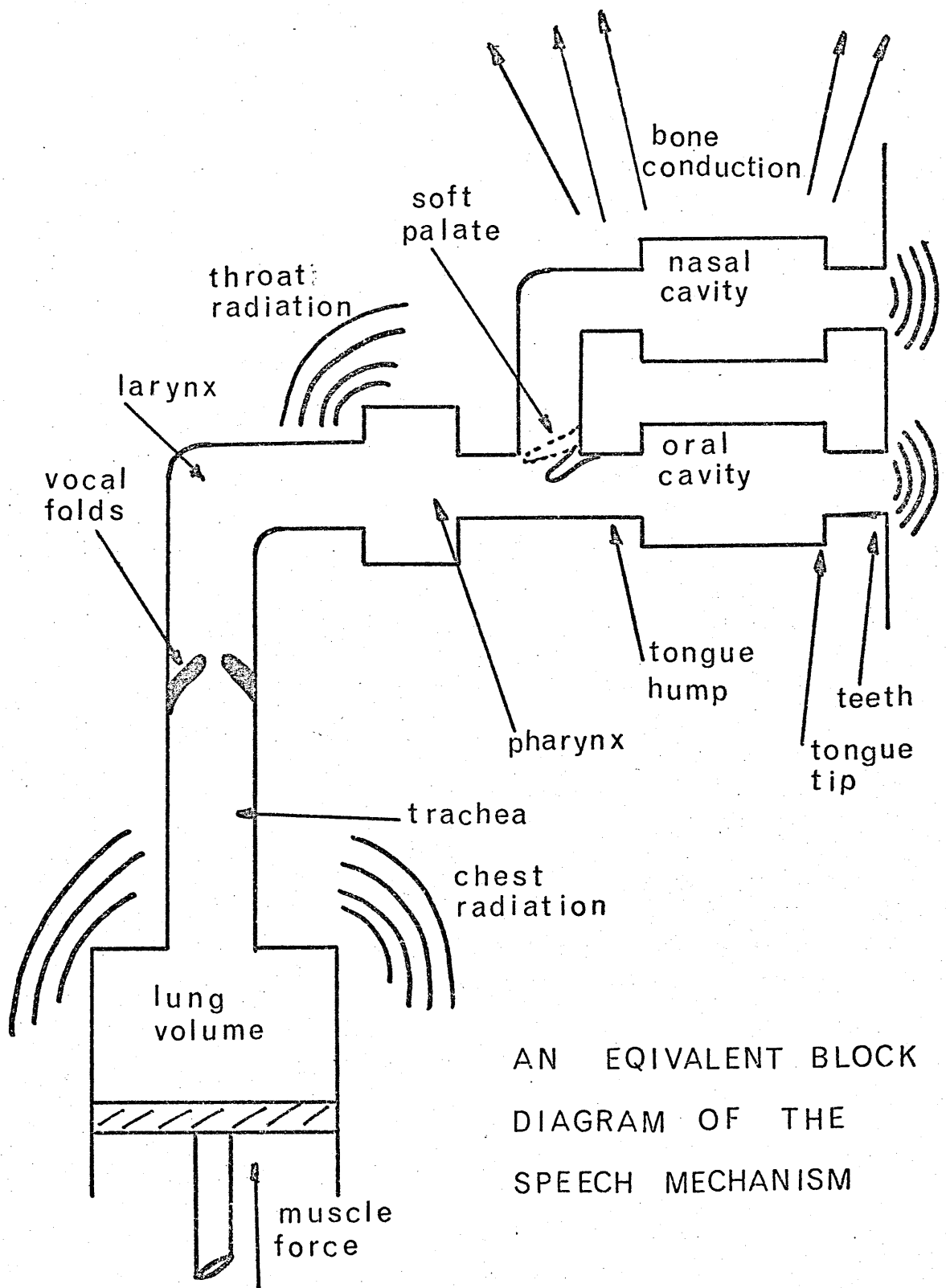
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CHAPTER ONESPEECH AND HYPERNASALITY1.01 SPEECH.

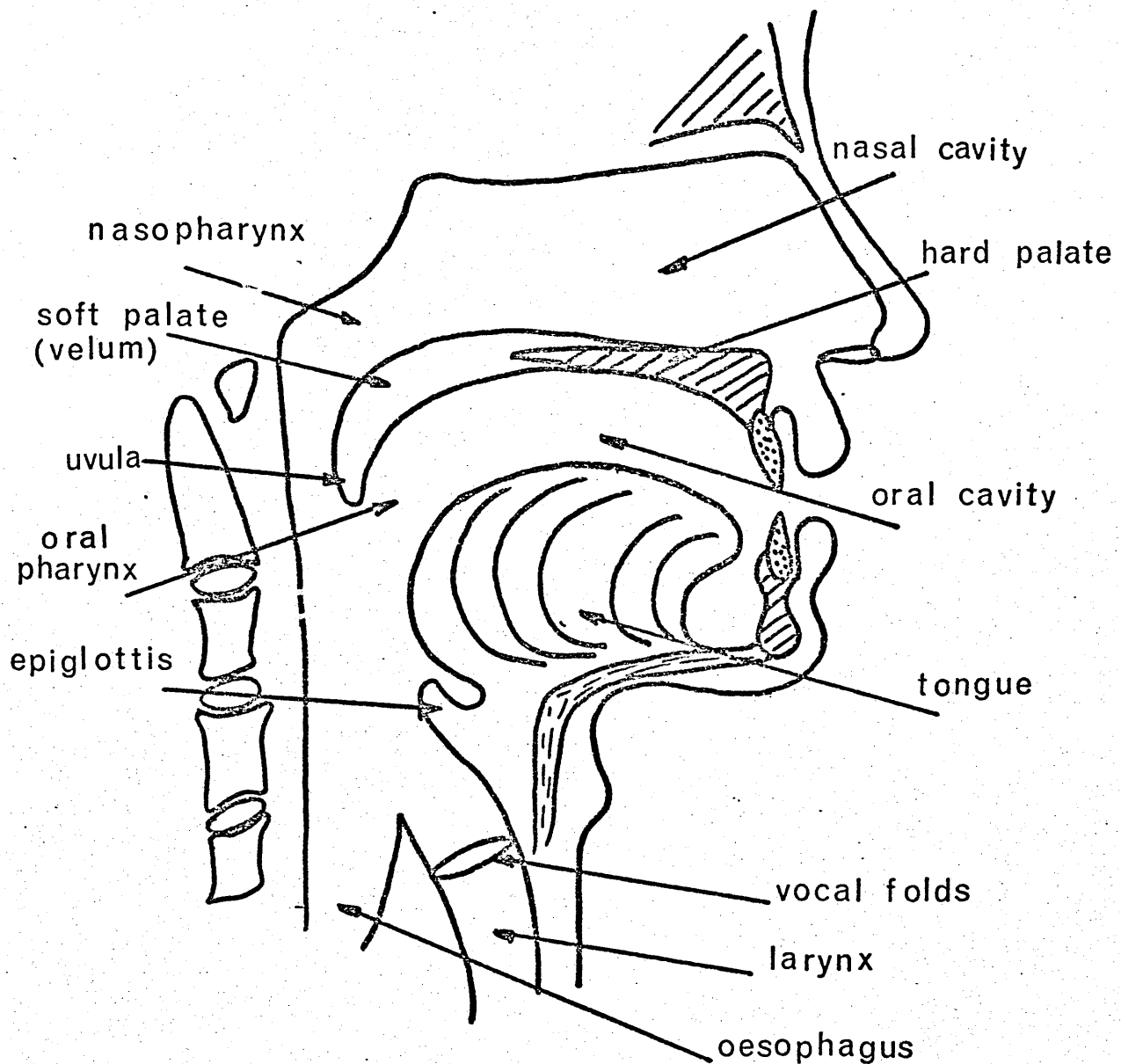
The voice is the basis of communicative speech and the individual's need for articulate speech is vital in normal everyday life. The first stage in the development of speech is the association of certain sounds, words, with visual, tactile and other sensations aroused by objects in the external world. These associations are " stored " as memories. After definite meanings have been attached to certain words pathways become established between the auditory area of the cortex and the motor area for the muscles of articulation and the child attempts to formulate and pronounce words which he has heard. This act of verbal expression involves the co-ordinated action of a large group of respiratory, laryngeal, lingual, pharyngeal and labial muscles.

The voice results when air, under pressure, from the lungs causes the approximated vocal folds to open and close rhythmically. In this way air escapes through the glottis in pulses. The frequency of these pulses is varied by changes in the tension of the vocal folds. The alternate compression and rarefaction of the air is responsible for the sound waves producing the fundamental pitch of the vocal note. The cavities of the chest below and the pharynx, mouth and nose above the larynx provide universal resonators for all speech sounds. The infinite variety of modifications in size and shape provided by movements of the tongue make possible the use of these cavities as selective resonators (acoustic filters) for the



AN EQUIVALENT BLOCK
DIAGRAM OF THE
SPEECH MECHANISM

FIG. 1.1



SAGITTAL SECTION THROUGH NOSE,
MOUTH, PHARYNX AND LARYNX

production of the various speech sounds. A equivalent block diagram of the resonators and areas of sound radiation is shown in FIG.1.1. The vocal instrument was primarily designed for the purposes of mastication, deglutition and respiration (Negus, V.E. (1963)). The adaption of these vital reflex functions, described in detail in a later chapter, to the purposes of speech is one of the most remarkable features of human evolution.

There are many disorders of speech but the present subject is only concerned with one particular problem, hypernasality.

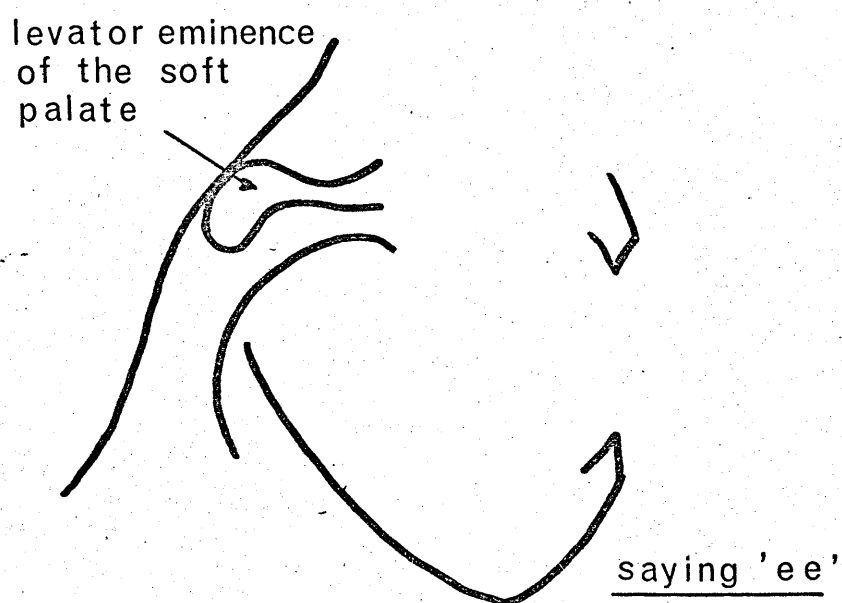
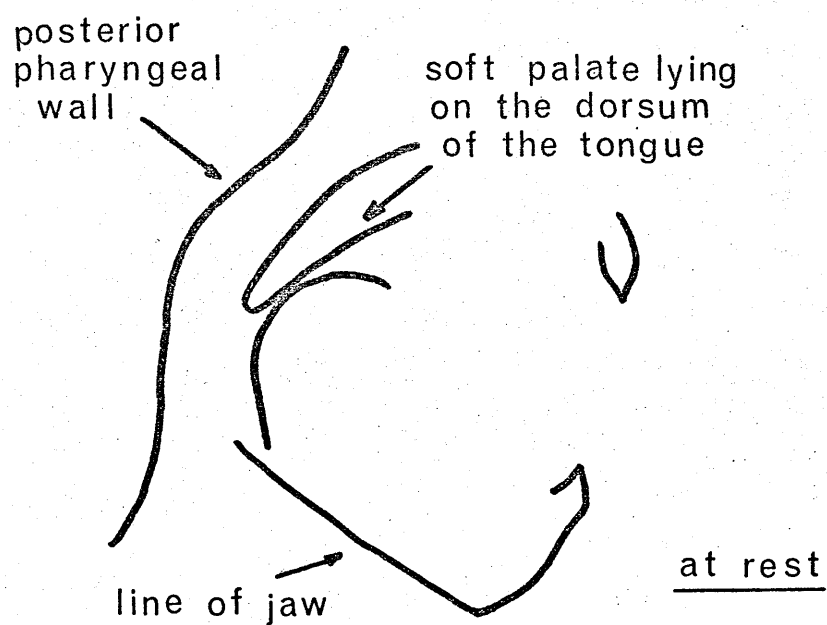
1.02 THE AETIOLOGY OF HYPERNASALITY.

In FIG.1.2 a sagittal section through the nose, mouth and pharynx shows the relative positions of the organs of articulation.

In normal speech the airway between the soft palate and the posterior pharyngeal wall is fully patent only during vocalisation of nasal consonants ("m", "n" and "ng"). To articulate the other consonants, especially the plosives and fricatives, it is necessary for the soft palate to elevate and close off this velopharyngeal isthmus.

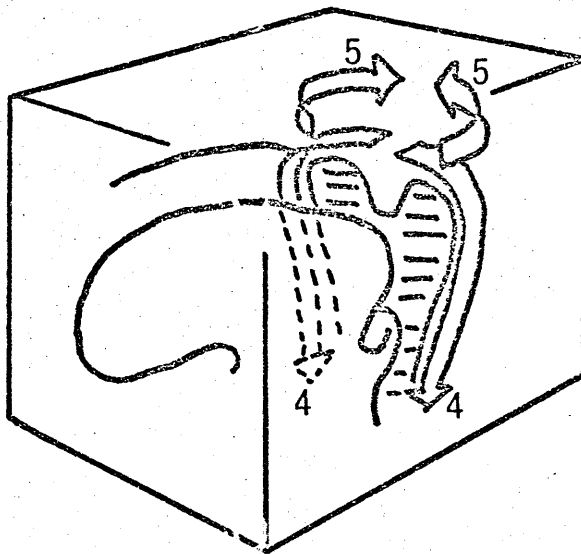
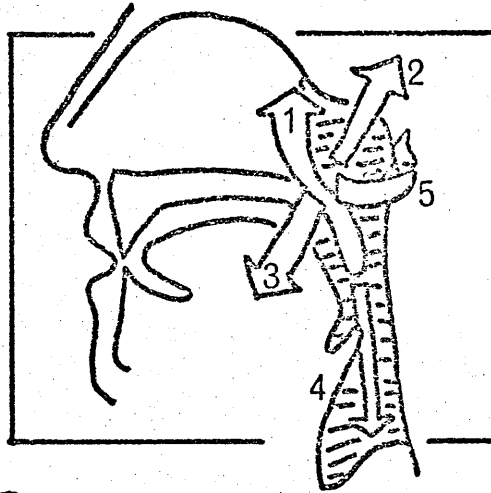
Hypernasality, gross, abnormal nasal escape of air from the nose during speech, has two main causes:-

- 1) A cleft of the hard or soft palate, that is, a hole directly connecting the oral and nasal cavities. This prevents the necessary increase in oral pressure for the adequate production of plosive and fricative consonants.
- 2) Limited or unco-ordinated movement of the soft palate (incompetence



radiographic tracings showing the
rest and lifted positions of the
soft palate

FIG. 1.3



- 1 TENSOR
- 2 LEVATOR
- 3 PALATOGLOSSUS
- 4 PALATOPHARYNGEUS
- 5 SUPERIOR
CONSTRICTOR

SCHEMATIC OF
THE VELOPHARYNGEAL
MUSCLES

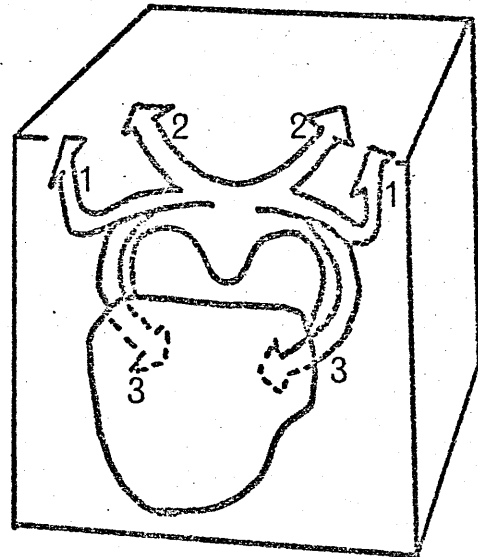


FIG. 1.4

of the soft palate). FIG. 1.3 shows the site of contact of the elevated soft palate with the posterior pharyngeal wall in speech . The soft palate is an entirely muscular structure forming a mobile flap which is attached to the posterior edge of the hard palate in front and hangs free behind. It is comprised of several pairs of muscles. These are described excellently by Fritzel,B. . FIG. 1.4 shows a schematic presentation of the velopharyngeal muscles and the approximate directions of their actions and influence on the soft palate. Dysfunction of this musculature may be due to lower motorneurone disease or to upper motorneurone disease originating in the brain stem or cerebral hemispheres. These may be congenital or acquired through a cerebral vascular accident or head injury.

1.03 TREATMENT OF CLEFT PALATE.

A cleft palate is treated as early as possible by plastic surgery, one or more operations being necessary depending on the extent of the fistula. It is often the case that incompetence of the soft palate remains post operatively.

1.04 TREATMENT OF INCOMPETENCE OF THE SOFT PALATE.

Until recently treatment has relied on techniques involving redirection of breath but the results of even prolonged and careful treatment frequently proved disappointing. In 1973/4 a new form of treatment was described by Tudor,C. and Selley,W.G. (1974) and Ellis,R.E. and Selley,W.G.(1973), which involves the use of a device, called a palatal training aid. This provides tactile stimulation of the soft palate. Also used is a training

aid providing a visual feedback of soft palate elevation, no matter how minimal. Using these aids many patients have acquired reasonable competence over periods of treatment ranging from three months to a year.

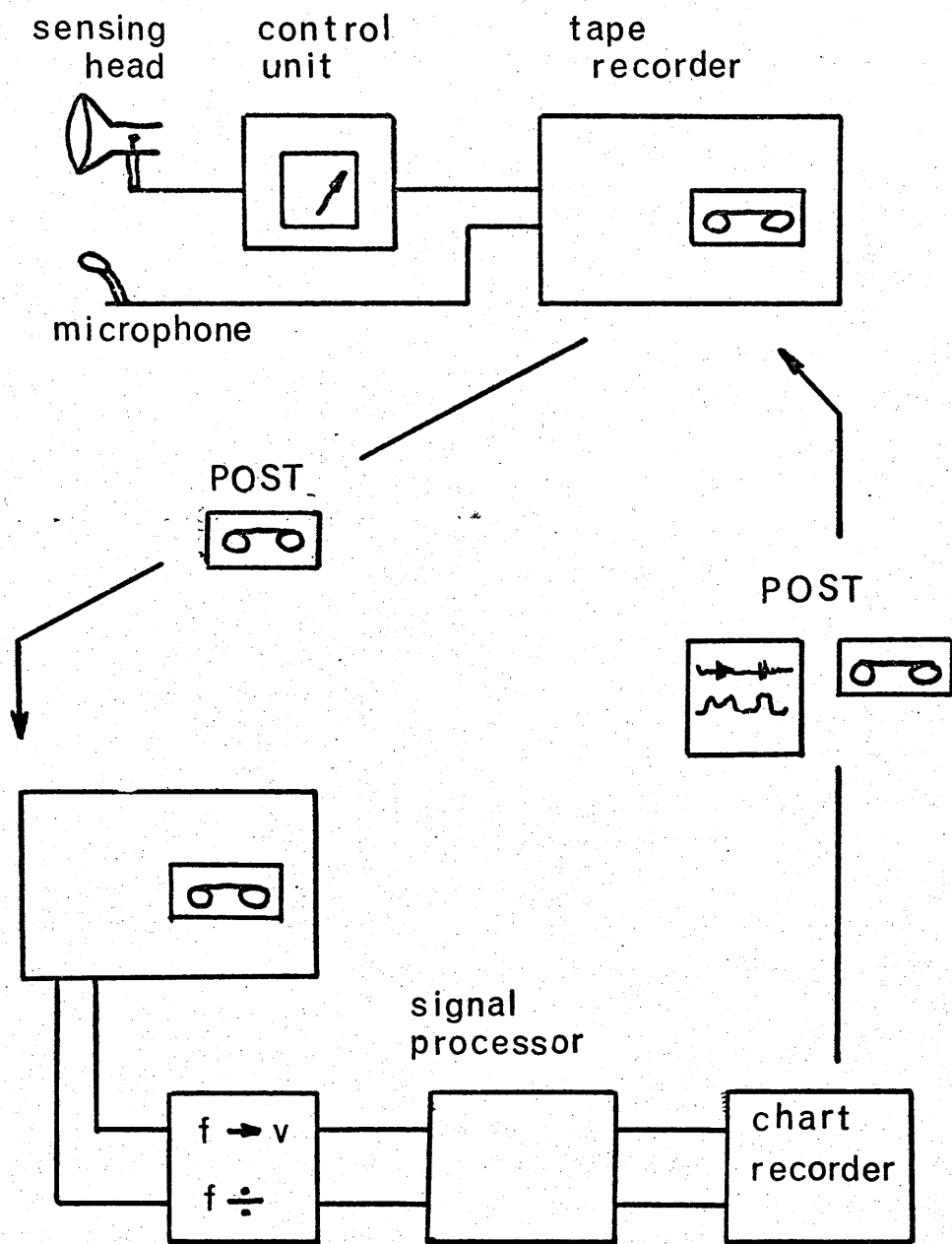
During the development of these techniques and the accompanying treatment programs it became obvious that several new methods of diagnosis and assessment of soft palate behaviour were needed. Two of these are subjects of this thesis.

CHAPTER TWOA SYSTEM FOR THE ASSESSMENT OF NASAL AIRFLOW DURING SPEECH .2.01 INTRODUCTION.

Many and various techniques have been used to detect the presence of nasal escape during speech, such as fogging a mirror, deflection of threads, tissue paper or soap bubbles placed in front of the nostrils. Panels of trained listeners and even experienced speech therapists are not always unanimous in assessing the amount of nasal escape. All these methods are very subjective and prevent comparison with previously made assessments, especially if these were made by another speech therapist. Because assessments of progress are often made over a period of several months, it is unlikely that the therapist will remember exactly the quantity and incidence of nasal escape in a given word, or in general speech, even if tape recordings are available.

There is a need for a device to measure nasal airflow objectively and, preferably, quantitatively. Nasal airflow meters (nasal anemometers) have been described by several authors, for example, Quigley, L.F. et al. (1965) and Warren, D.W. (1967) , and built in a number of research centres, but have the disadvantages that they are expensive, custom built devices and require the full technical back up facilities of a large department to be available at the time of assessment. Accordingly only specialised studies with such devices have been made and none of them have become tools available to smaller departments or to individual speech therapists.

The first part of this thesis describes such a



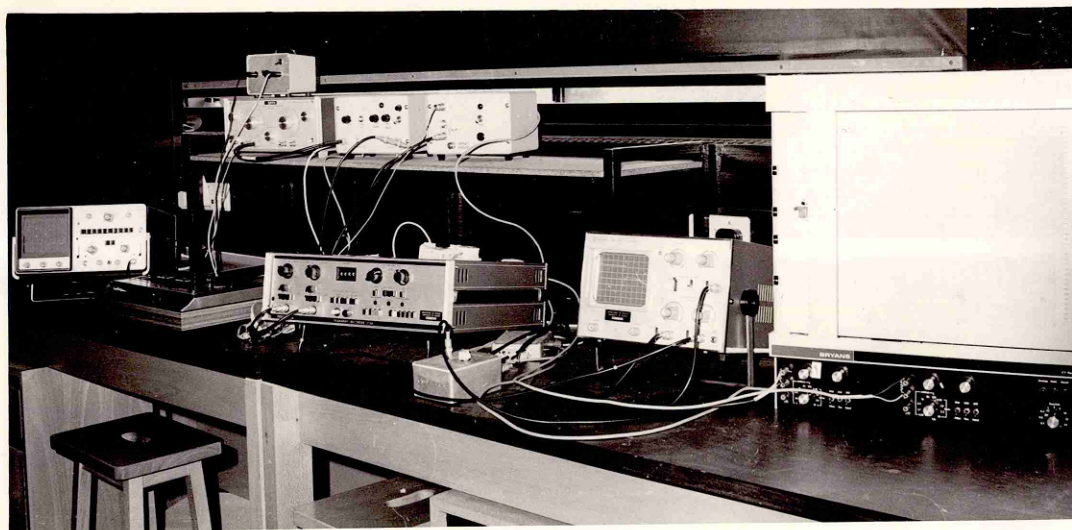
schematic of the anemometer system

FIG. 2.1



THE RECORDING APPARATUS.

FIG. 2.2(a)



THE CHART PROCESSING APPARATUS.

FIG. 2.2(b)



A SUBJECT MAKING A RECORDING.

FIG. 2.3

device capable of quantitative assessment of nasal airflow simultaneously with speech, without restricting this airflow.

2.02 AN OVERALL VIEW OF THE SYSTEM.

The apparatus is in two parts. The expensive processing equipment can process data from a large number of therapists. The less expensive recording equipment is held by the therapists for use in their clinics. With the latter, airflow and speech are recorded simultaneously on different tracks of a stereo cassette tape recorder of the type used for home entertainment. The cassette is then sent, by post, to the processing centre where the tape is processed to provide charts. These are returned to the therapist with the original cassette. Comparison can be made with data from large numbers of subjects with "normal" speech. It is possible to diagnose the occurrence of abnormal nasal escape and thus provide the therapist with an exact assessment and a permanent record of any improvement as a result of a particular regime of treatment for hypernasal speech.

FIG.2.1 is a schematic layout of the apparatus presented in FIGs.2.2(a) and 2.2(b). The sensing head measuring the airflow is a thermistor mounted in a standard, rubber anaesthetic mask. Nasal airflow is measured by placing the mask over the nose of the subject (FIG.2.3) and the subject asked to repeat single words or short phrases. The exit from the mask is a tube, which carries the thermistor and allows nasally inhaled and exhaled air to flow in an unrestricted manner. For very young patients, unhappy to tolerate the mask, a small hand held under nose piece, which does not enclose the nose, may be used. This

does not provide such accurate quantitative data as the mask, shown in detail in a later chapter, but experience suggests that tracings from it display many of the characteristics revealed by the mask-mounted equipment.

A meter, mounted on the front of the anemometer control box, gives an immediate indication of airflow at the time of making a recording. However it has been found difficult, in practice, for one operator to make a recording and estimate accurately the instantaneous airflow. The meter is, nevertheless, useful to check the equipment, to give an approximate indication of airflow and to assist the patient during therapy. Final assessments are always made using charts.

When the recorded tape arrives at the processing laboratory, decoding and digitising equipment allows an ordinary chart recorder to print out the two channels of information, viz the speech sounds and immediately below and correlated with the speech, the airflow. These prepared charts are returned, with the cassette, to the speech therapist who may listen to the speech as a guide to interpretation of the chart.

The details of the development and choice of associated equipments are discussed in the following sections of this chapter:

2.03 Discussion of sensing systems, tape recorders and charting apparatus.

2.04 to 2.09 Sensing head, thermistors, circuits for thermistors and calibrations.

2.10 Tape recorder and voltage to frequency converter.

2.11 and 2.12 Frequency to voltage converter, transient signal processing and the chart recorder.

2.03 DISCUSSION OF SENSING, RECORDING AND CHARTING SYSTEMS.

a) SENSING SYSTEMS.

There are several types of airflow sensor available. For use in nasal anemometry there ^{are} some important design specifications. The device should be safe for use by patients, have a low flow resistance and be rugged but small and lightweight.

Physically large sensors, such as pitot tubes, are of course unsuitable for nasal anemometry. Those ideally suited are the hot wire, heated film and thermistor types. The hot wire flowmeter, because of its small thermal capacity is the most sensitive but, because the hot tungsten filament would react with the water in the expired air, it is also unsuitable. The heated film type of sensor is expensive and therefore the thermistor was chosen as the sensing element.

The thermistor fulfills the main criteria listed previously, the voltages, used in the Wheatstone bridge circuit, are low and its dimensions (FIG. 2.4) are such that it scarcely interferes with the airstream. Problems arising from its high running temperature, 180°C , are overcome in the mounting system, but its thermal capacity is so small that serious damage from accidentally touching the hot bead is impossible.

b) TAPE RECORDING SYSTEMS.

The electrical signals from the anemometer circuits consist of voltages which slowly change at a maximum frequency of 10 Hz. Because the low-frequency response of a typical tape recorder, using amplitude modulation, is of the order of 30 Hz a frequency-modulated recorder would be preferable. Frequency-modulated instrumentation-recorders are very expensive and cannot therefore be considered for issue to each therapist. An alternative

is to make a domestic tape recorder into one accepting f.m. signals by use of a voltage controlled oscillator in the anemometer control circuit. Cross talk levels suitable for data recording are important because breakthrough of the voice channel could produce artifact on the airflow printout and breakthrough of the frequency modulated data signal makes defining the beginning and end of words on the voice chart virtually impossible.

Following detailed examination of cassette recorder specifications, an Amstrad 7050 was chosen for trials. The crosstalk on this recorder was measured, for signals of typical amplitude, and compared with the performance of other makes of similar quality under identical conditions. Crosstalk was measured using the following technique: the output, at 1 kHz and 1 mV peak to peak, from a signal generator was connected to the left channel microphone input of each recorder in turn and recorded for one minute. The line outputs, ie before power amplification, on left and right channels for each recorder were then measured during playback, with the following results.

MAKE	LEFT CHANNEL V p.t.p.	RIGHT CHANNEL V p.t.p.	CROSSTALK dB down
Amstrad 7050	1.5	0.01	43
Akai GXC39	1.5	0.02	37
Sony TC124	0.1	0.01	20

For these tests and for all subsequent trials ferric-oxide low-noise recording tape was used.

c) CHART RECORDING SYSTEMS.

The frequency response of most pen type chart

recorders is low, usually in the range 1 to 100 Hz. This is high enough for faithful reproduction of the airflow signals but voice frequencies can approach 16 kHz with most content around 200 Hz. The only types of dual-channel chart recorders that have frequency responses of this order are the Mingograph ink-jet writer and the U.V. lightwriter. The Mingograph is very expensive and has not a very high frequency response. There are, however, also disadvantages in the use of the U.V. writer. The special light sensitive paper has a poor shelf-life, is very expensive and, unless chemically fixed, the resultant charts fade in a matter of days unless rolled and kept away from light.

The system chosen for charting the anemometer recordings is the combination of a transient signal processor and a flat-bed chart recorder with a capillary pen. The transient signal processor consists of an analogue to digital converter to digitise the incoming data prior to storage in a memory. Information can thus be taken in at high frequencies and later relayed, through a digital to analogue converter, at a rate to suit the standard flat-bed pen-recorder.

Experience has shown that ten seconds is a convenient period of recording, and this reduces the frequency response of the whole system to 40 Hz. This could be improved by increasing the memory available from 2000 words per channel or by shortening the period of recording. The frequency response for single words in two seconds of recording is 200 Hz and the system can be used in this way if greater definition is required.

P 15
THERMISTOR

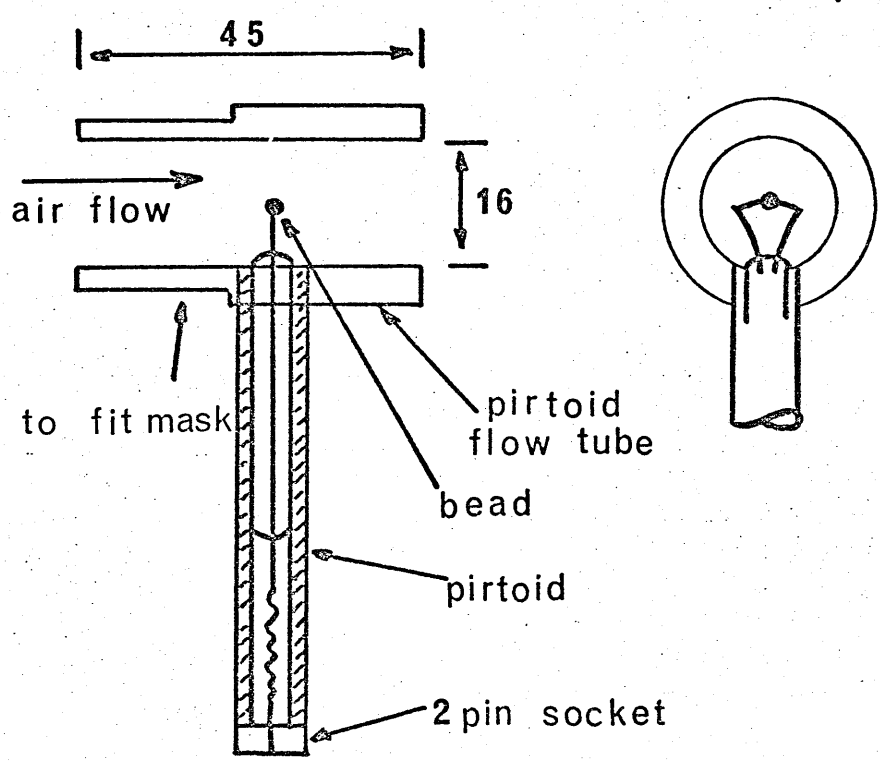
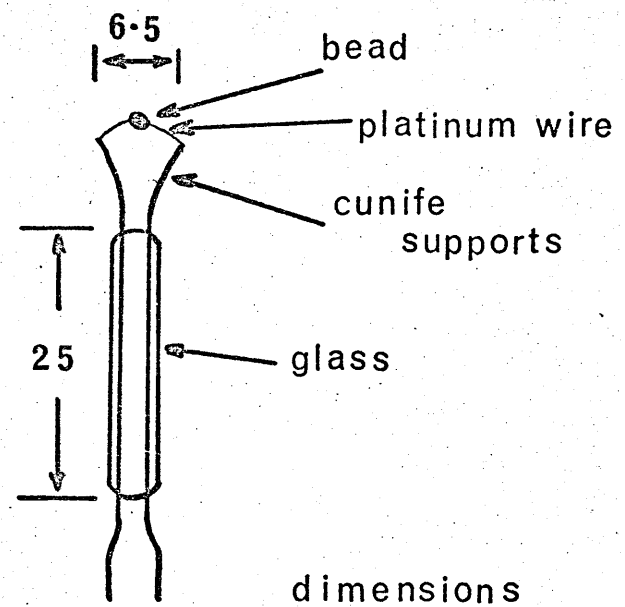
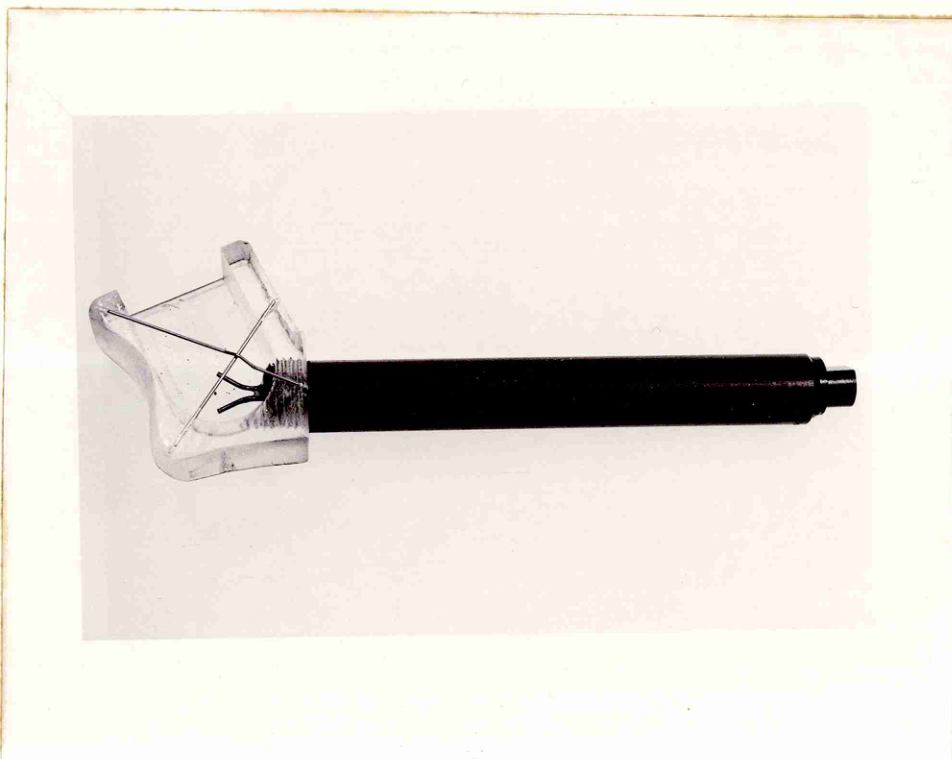


FIG. 2.4



THE MASK AND FLOW TUBE.

FIG. 2.5(a)



THE UNDERNOSE PIECE.

FIG. 2.5(b)

2.04 THE DESIGN OF THE SENSOR HEADS.

FIG 2.4 shows the ITT P15 thermistor, chosen for use in the sensing head, its dimensions and the method of mounting into the anemometer head. The thermistor is cemented into its support tube which is in turn screwed into the flow tube. The flow tube (FIG. 2.5 (a)) is easily detached from the rubber mask so that the latter may be easily sterilised. FIG. 2.5(b) shows the constructional details of the undernose piece.

The pressure drop across the flow tube was measured at various flow rates to establish whether it would create a back pressure in the nasal passages and therefore give a false reading of flow. The tube resistance was found to be negligible; producing a pressure drop of only 0.25 kN/m^2 at a maximum flow of $40 \text{ L/min}^{\text{sec}}$, compared with 1 kN/m^2 at $1 \text{ L/min}^{\text{sec}}$ for the nose (Warren and Dubois (1964)).

2.05 THE THERMISTOR.

The negative temperature coefficient (n.t.c.) thermistor is a temperature sensitive bead of semiconductor whose resistance decreases as its temperature increases, it possesses a high coefficient of resistance, typically -4% per degree centigrade at 20°C . Like other semiconductor components it is a reliable device and has good long-term stability.

The resistance, R_{t1} , at temperature $T_1^\circ\text{K}$ can be related to the resistance, R_{t2} , at any other temperature $T_2^\circ\text{K}$ by the following equation:

$$R_{t1} = R_{t2} \cdot e^{(B/T_1 - B/T_2)} \quad (1)$$

where B is the characteristic temperature of the thermistor,

expressed in Kelvin.

From equation (1) :-

$$B = \frac{T_1 \cdot T_2}{T_1 - T_2} \log_e \frac{(R_{t2})}{(R_{t1})}$$

For most thermistors the variation of B with temperature is small enough to assume that it is constant between ambient and its maximum working temperature.

When electrical power is dissipated within the thermistor it is said to be self-heated and its temperature can be considered to increase by an amount proportional to its dissipation constant, K' , which is defined as the power required to raise the thermistor temperature by 1°K and is determined by the construction of the thermistor and its operational environment. The power dissipated is given by:-

$$P = V \cdot I = K' \cdot \Delta T \quad (2)$$

where:-

P = power dissipated, Watts.

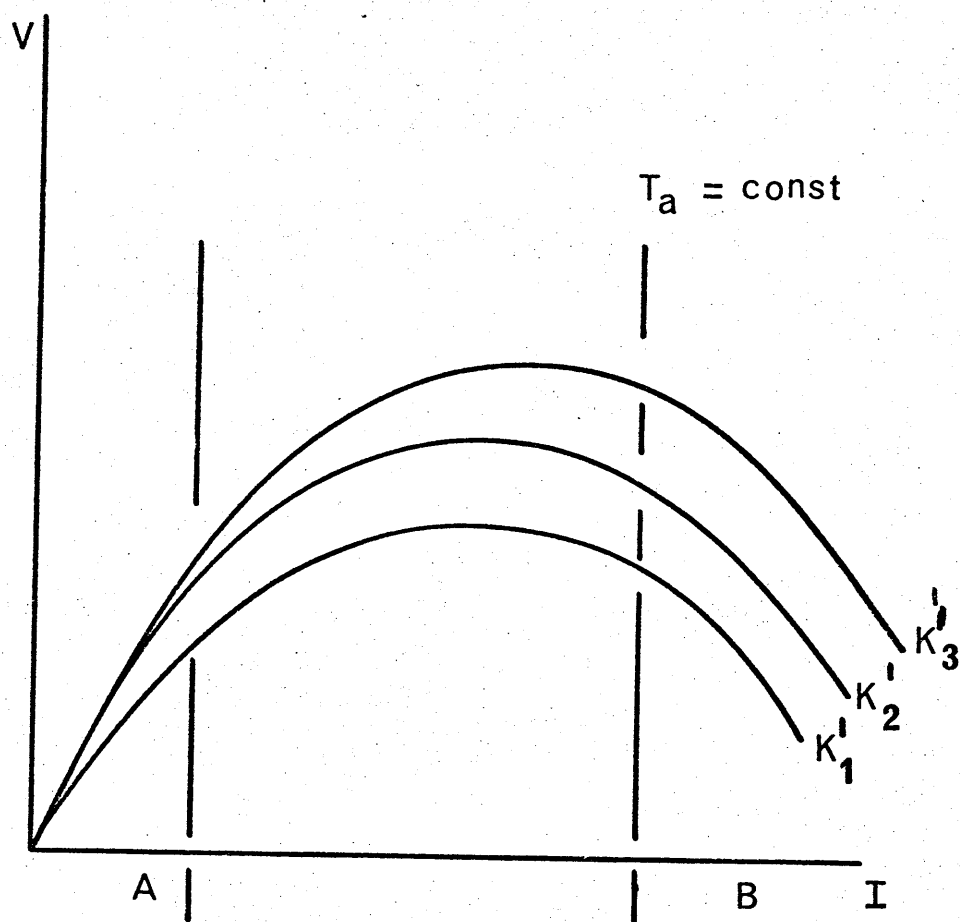
V = voltage across thermistor, Volts.

I = current flowing through thermistor, Amps.

K' = dissipation constant, Watts/ $^\circ\text{K}$.

ΔT = temperature difference between ambient and the thermistor bead, $^\circ\text{K}$.

(K' is often expressed in mW/ $^\circ\text{K}$)



V/I characteristic for
different airflow rates

FIG. 2.6

Equation (2) can be rewritten :-

$$P = K' (T - T_a) \quad \text{-----} \quad (3)$$

where :-

T = the bead temperature

T_a = ambient temperature.

The use of the steady state relationship shown in equation (3) assumes Newtonian cooling. K' is independent of T for $(T - T_a) \ll T_a$; for larger values of $(T - T_a)$ it is necessary to use the more complicated relationship of Smith, O.J.M. (1950). It must be noted that K' is markedly influenced by ambient conditions and is therefore only constant in situations where these conditions remain unchanged.

Thermistors used for anemometry are operated in this self heated mode. The temperature of the bead is kept constant and variations of the power dissipation used to monitor changes in the ambient conditions.

A family of Voltage/Current characteristics can be generated for a given, fixed ambient temperature and variations of K' due to changes in airflow velocity (FIG. 2.6).

The two regions A and B marked on FIG. 2.6 show the possibilities of the two modes of operation of the thermistor. Region A, where negligible self heating occurs, is used for thermometry. Region B exhibits maximum sensitivity to variations in ambient conditions, especially airflow if T_a is constant.

The power dissipation is, however, limited to defined maximum ratings. As shown earlier when the current through an n.t.c. thermistor is increased, the voltage across the bead at first rises rapidly and soon attains a maximum value E_{\max} ,

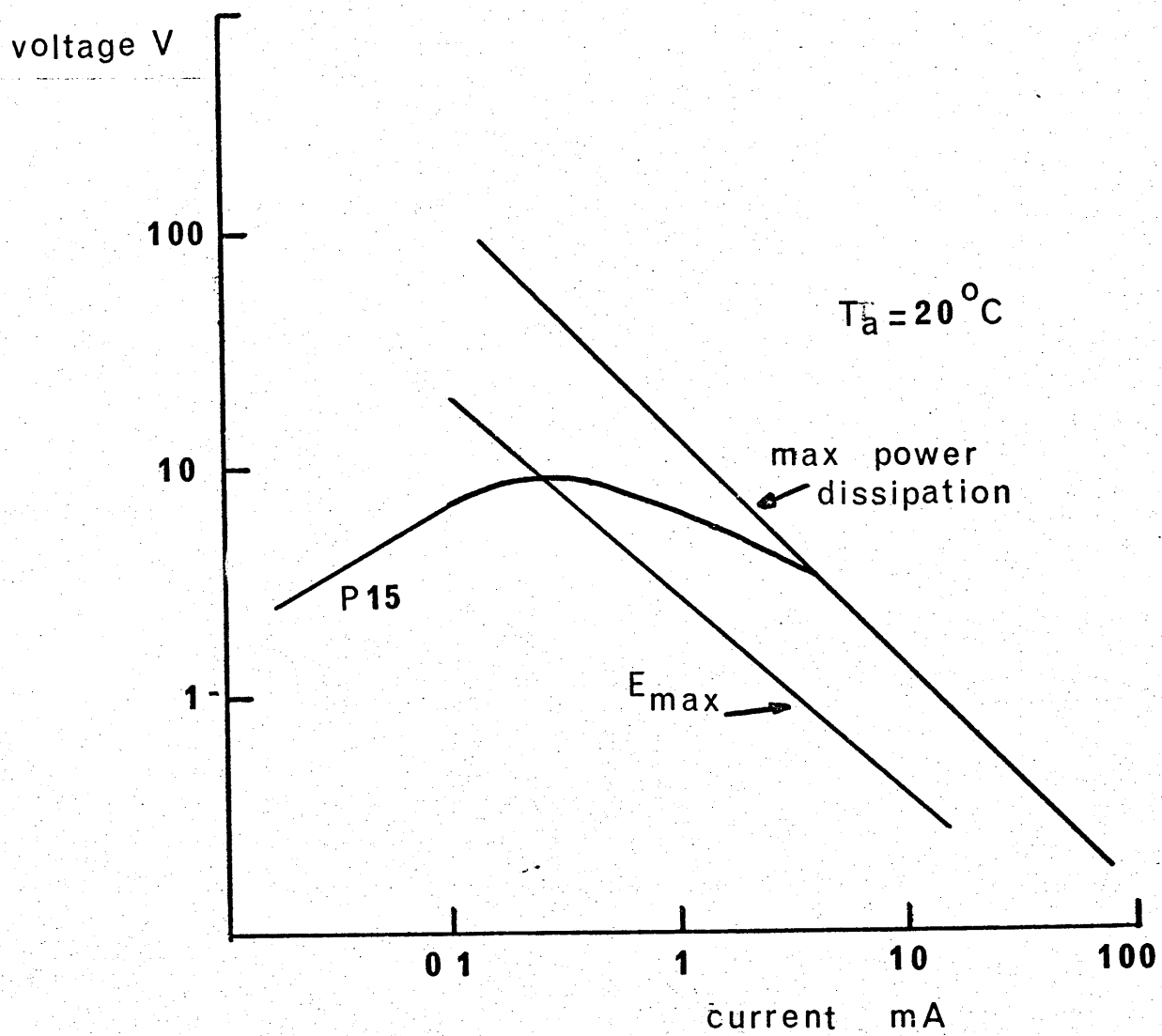
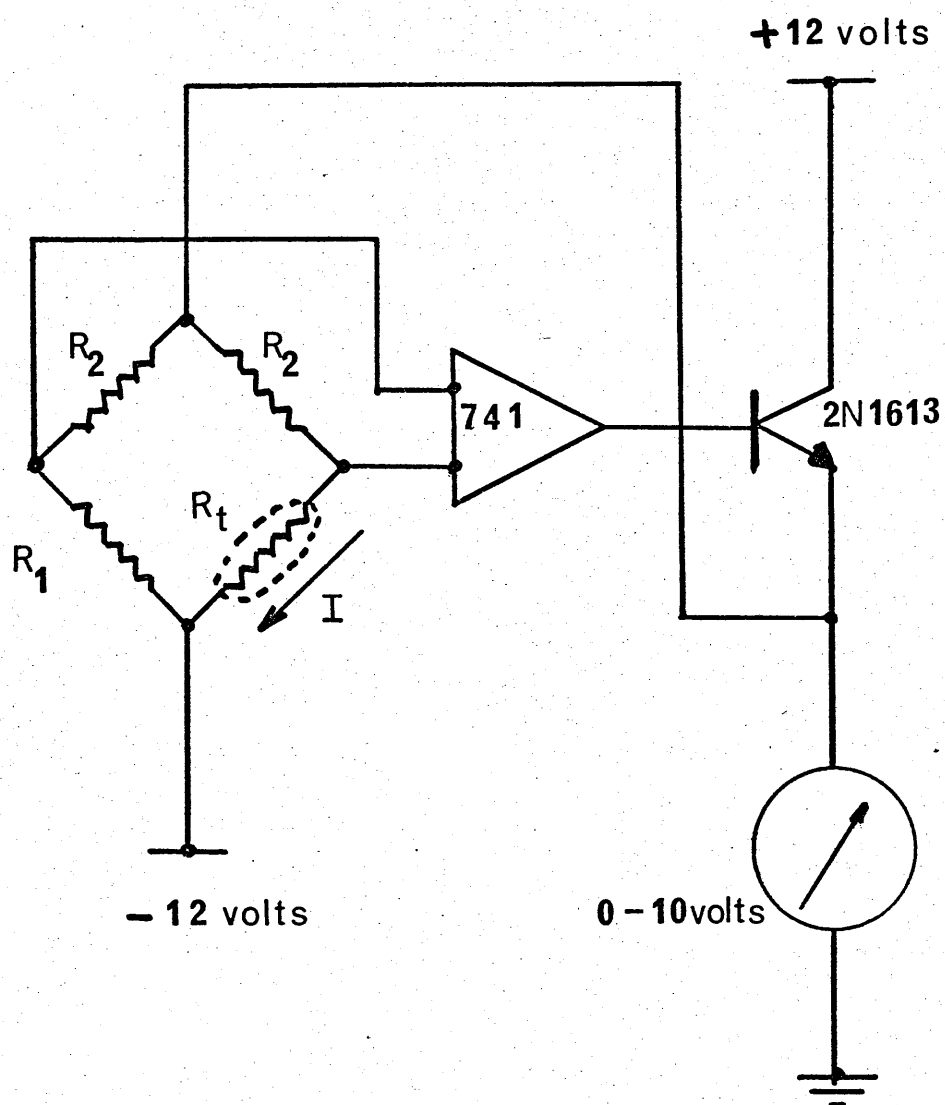


FIG. 2.7



self balancing thermistor bridge

FIG. 2.8

shown in FIG. 2.7. Thereafter it behaves as a negative slope resistance and there is a decrease in voltage with further increase in current. If the current is increased beyond the point where the V / I curve intersects the maximum power dissipation curve the thermistor will "run away".

From the I.T.T. Components data sheet:-

$$E_{\max} \propto \frac{R_a \cdot K'}{B} \quad (4)$$

where :-

R_a = the resistance at ambient temperature.

It can be seen from equation (4) that E_{\max} will decrease with increasing temperature.

Some thermistors are quite large, glass encapsulated devices, but those used for anemometry are normally "nude" elements supported on very fine platinum wires. The lack of glass encapsulation improves the power dissipation and response time.

2.06 THE ANEMOMETER CIRCUITS

a) THE SELF BALANCING BRIDGE CIRCUIT.

To measure flow, as previously discussed, the thermistor is used in the self-heat mode. To obtain maximum sensitivity it is necessary to use as high a thermistor temperature as possible. Constant manual balancing of the bridge, necessary at these levels, would render the system impractical. The self balancing bridge, shown in FIG. 2.8, is therefore used as the basic anemometer circuit.

A current I flows in one limb, sufficient to heat the bead so that its resistance is R_t . The bridge is balanced for this value R_t and as the bead resistance is uniquely determined by its temperature, if the bridge remains balanced then the bead temperature will be constant.

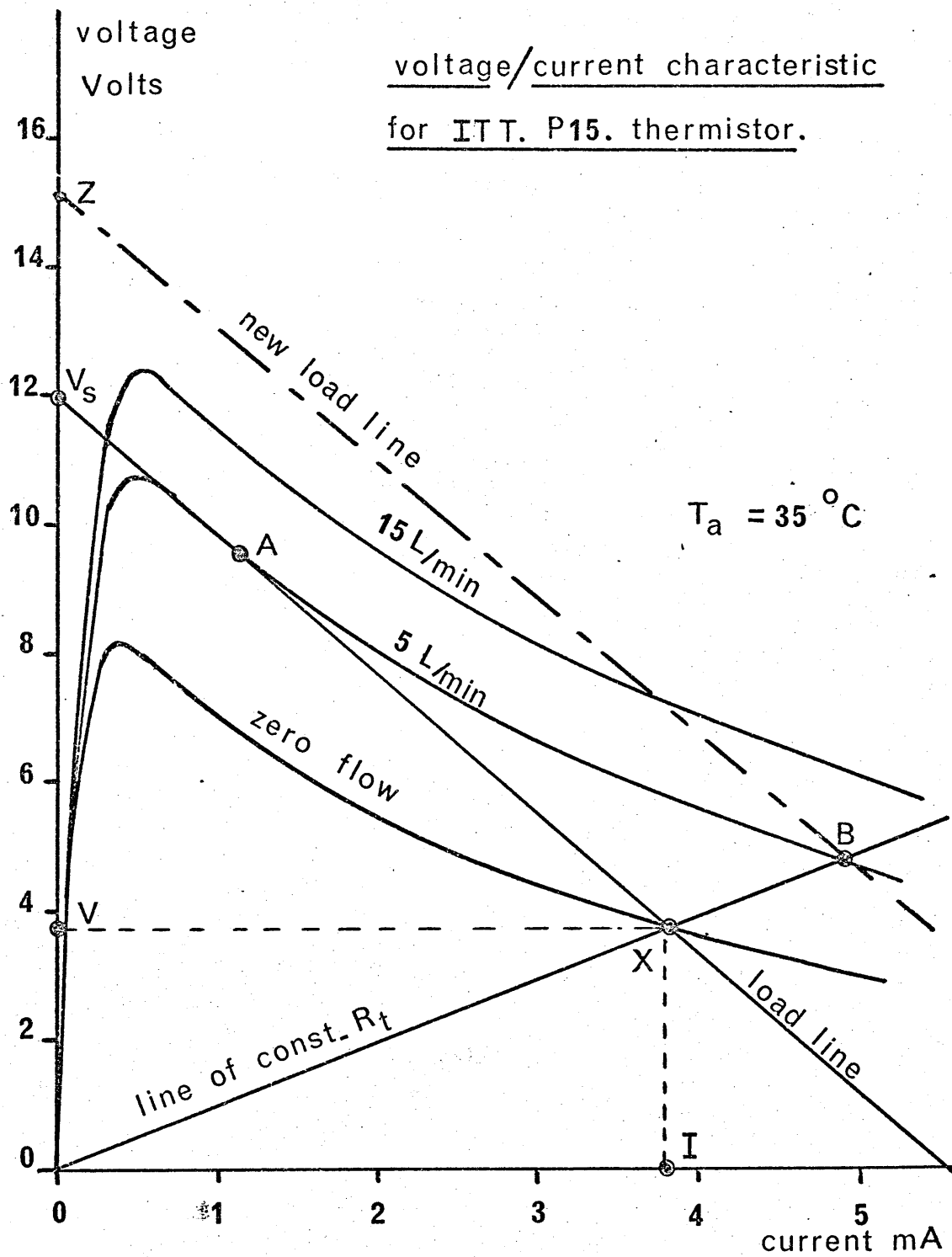


FIG. 2.9

The imbalance voltage from the bridge is applied to a differential amplifier and, through a current booster, back into the bridge to correct the imbalance condition. The circuit is always in dynamic equilibrium and the voltage output of the amplifier is related to the power dissipation of the thermistor.

b) SELECTING THE OPERATING POINT AND BRIDGE RESISTOR VALUES.

Using:-

$$P = K' (T - T_a)$$

we see that the effects of ambient temperature fluctuations are minimised if $T \gg T_a$. From manufacturer's data sheet for the I.T.T. F15 thermistor:-

$$T_{\max} = 180^\circ\text{C}$$

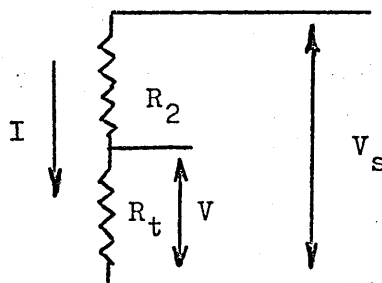
$$R_{\min} = 1030$$

$$P_{\max} = 14 \text{ mW.}$$

Therefore for a balance condition of the bridge a resistor of approximately $1\text{k}\Omega$ is required in the arm adjacent to the thermistor to provide an operating temperature of 180°C . This resistor is shown as R_1 in FIG.2.8.

FIG.2.9 shows experimentally determined V/I characteristics for the chosen thermistor. Using these curves it is possible to choose the operating point and calculate the value of R_2 in the bridge.

Using the following nomenclature for one arm of the bridge shown in FIG.2.8:-



From the diagram on the previous page :-

$$V = V_s - I \cdot R_2 \quad \text{-----} \quad (5)$$

As already stated $R_t = 1 \text{ k}\Omega$. OX in FIG. 2.9 is the line of constant R_t . That is the V / I characteristic of $R_t = 1 \text{ k}\Omega$ and X is the zero flow operating point. The load line for a fixed value of V_s can then be constructed. Equation (5) is that of the load line, with intercepts on the axes at V_s and

$$I = V_s / R_2.$$

If airflow cools the bead the operating point moves along the load line to point A, the intersection with the V / I curve for the appropriate flow. The feedback to the bridge changes V_s returning the operating point to B along line AB, thus balancing the bridge. Point B is the intersection of the line of constant R_t and the new V / I curve. If a new load line were constructed it would lay along BZ, parallel to the original load line but with a new value of V_s .

The value of R_2 is obtained by using the parameters of the no flow operating point to solve equation (5).

$$\begin{aligned} V &= V_s - I \cdot R_2 \\ 3.8 &= 12 - 3.8 R_2 \\ \underline{R_2} &= \underline{2.15 \text{ k}\Omega} \end{aligned}$$

In practice the manufacturers figures are only nominal and some adjustment of R_1 and R_2 may be necessary to achieve a satisfactory zero flow operating point.

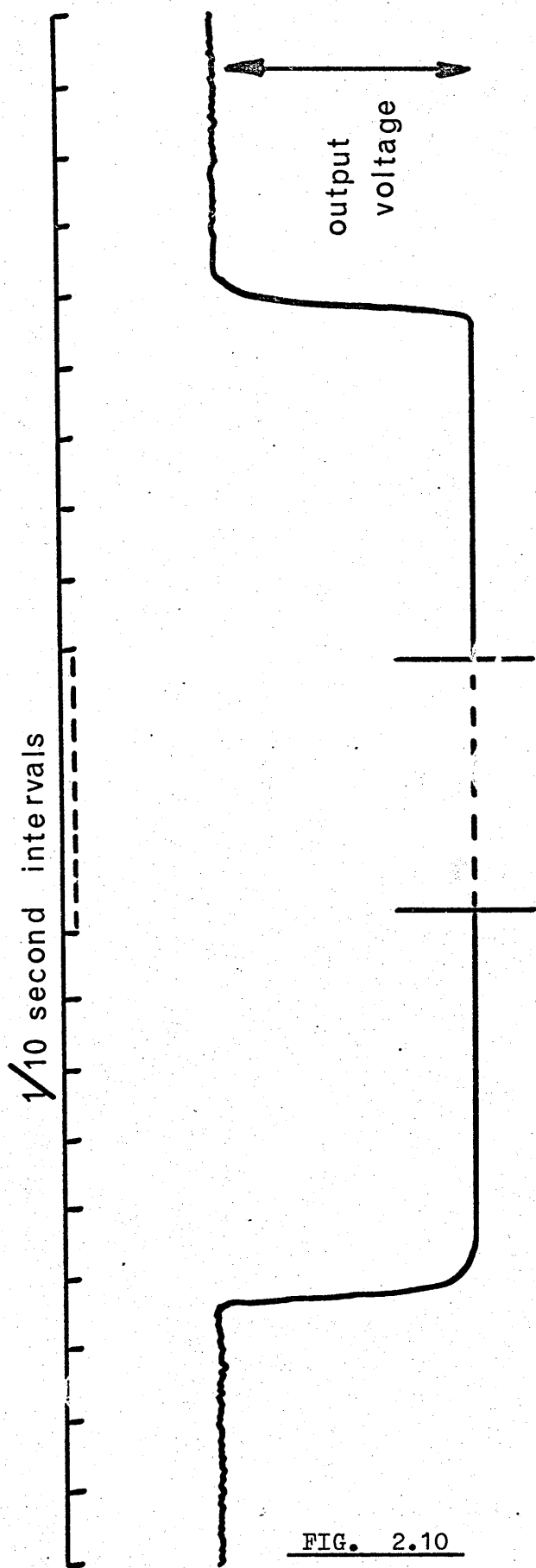
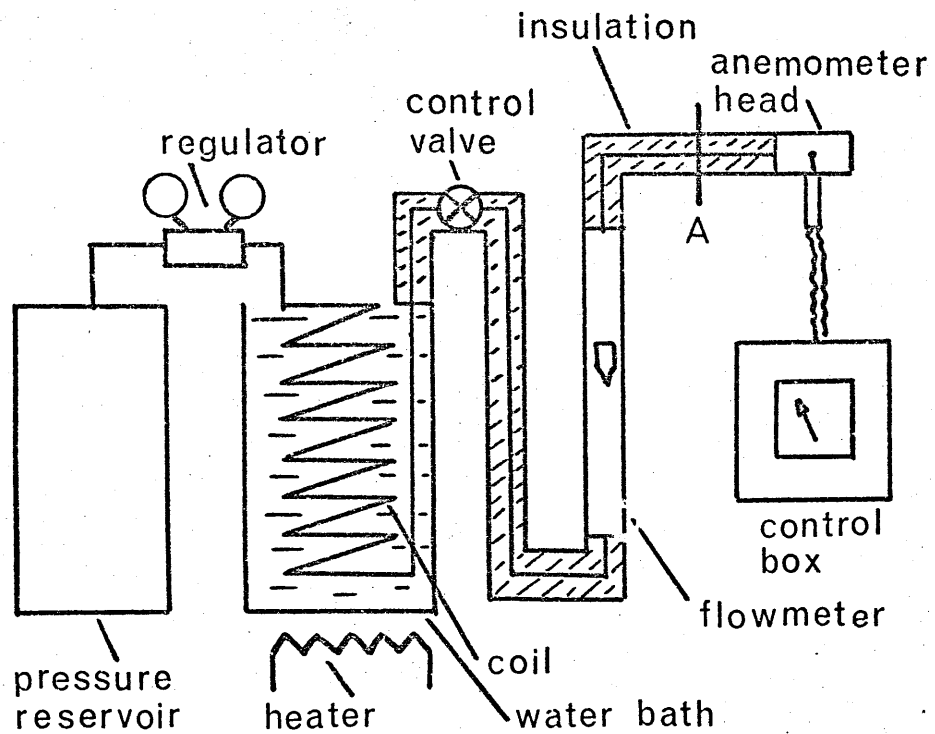


FIG. 2.10

THERMISTOR RESPONSE TO RAPID
FLOW CHANGE



schematic of flow calibration circuit

FIG. 2.11(a)

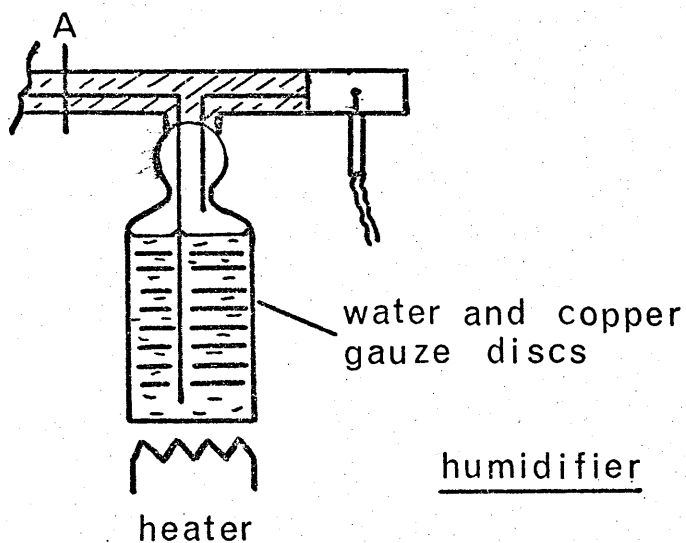


FIG. 2.11(b)

2.07 THE THERMISTOR RESPONSE TIME.

Other researchers in our laboratory have made measurements of the response times of the P15 thermistor running at temperatures of 170 to 180 °C by moving a thermistor rapidly from an airstream of one speed to another at the same temperature but of different speed. After a time the thermistor was returned to the original stream. FIG. 2.10 shows that the time taken for the thermistor temperature to stabilise in each airstream is no longer than 35 milliseconds, which is the time taken to transport the bead between airstreams.

The response time is thus adequate for nasal anemometry where the most rapid changes in airspeed take about 100 milliseconds.

2.08 FLOW CALIBRATIONS.

To calibrate the thermistor head for various conditions of flow and temperature it was necessary to construct equipment to provide a steady stream of air, of variable speed from 0 to 50 ^{Litres}~~metres~~ ^{minute}~~per second~~, plus a means to measure this to within a few percent. It was also necessary to be able to alter the temperature of this airstream over a range from room temperature to about 40 °C, ie a little above the normal body temperature.

FIG. 2.11(a) is a flow diagram of the apparatus consisting, basically, of a tank of air at an elevated pressure connected to a long coil of copper tubing which acts as a heat exchanger. The tubing is immersed in a tank of water, whose temperature may be accurately controlled to within 0.5 °C. The flow is measured using Rotameter flowmeters. These have an

anemometer output / flow

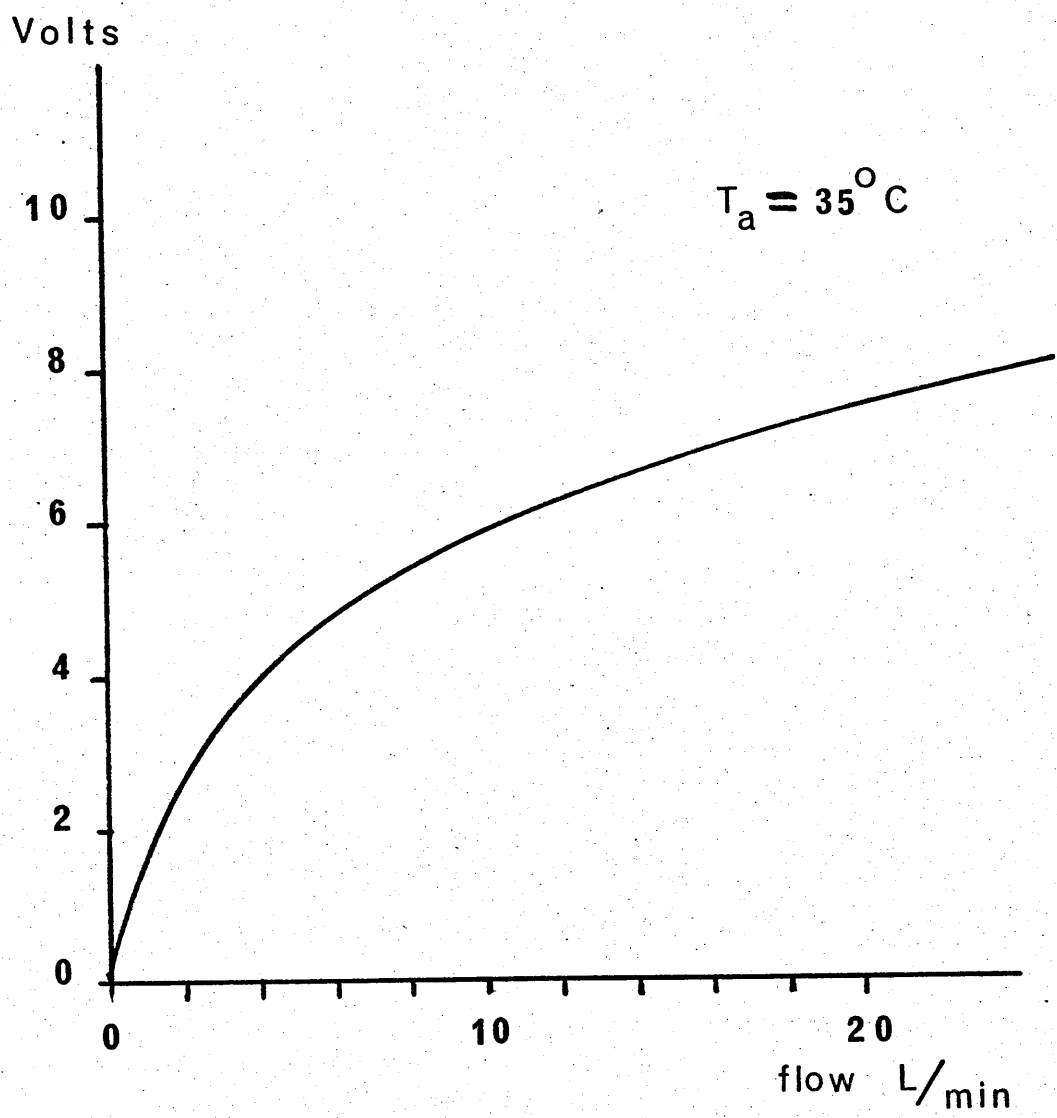


FIG. 2.12

chart deflection above zero / flow

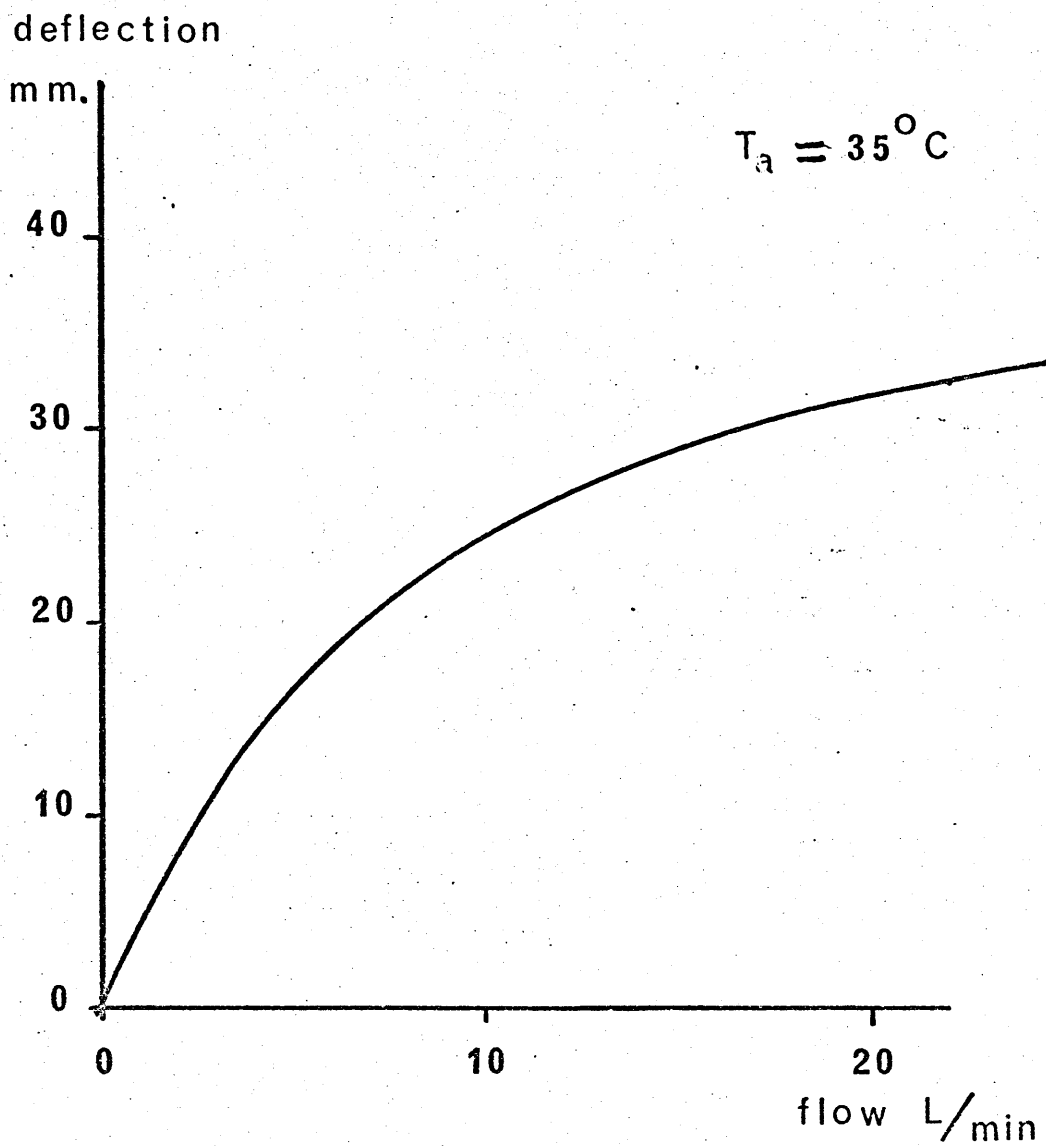


FIG. 2.13

variation in chart deflection
for 3 different heads.

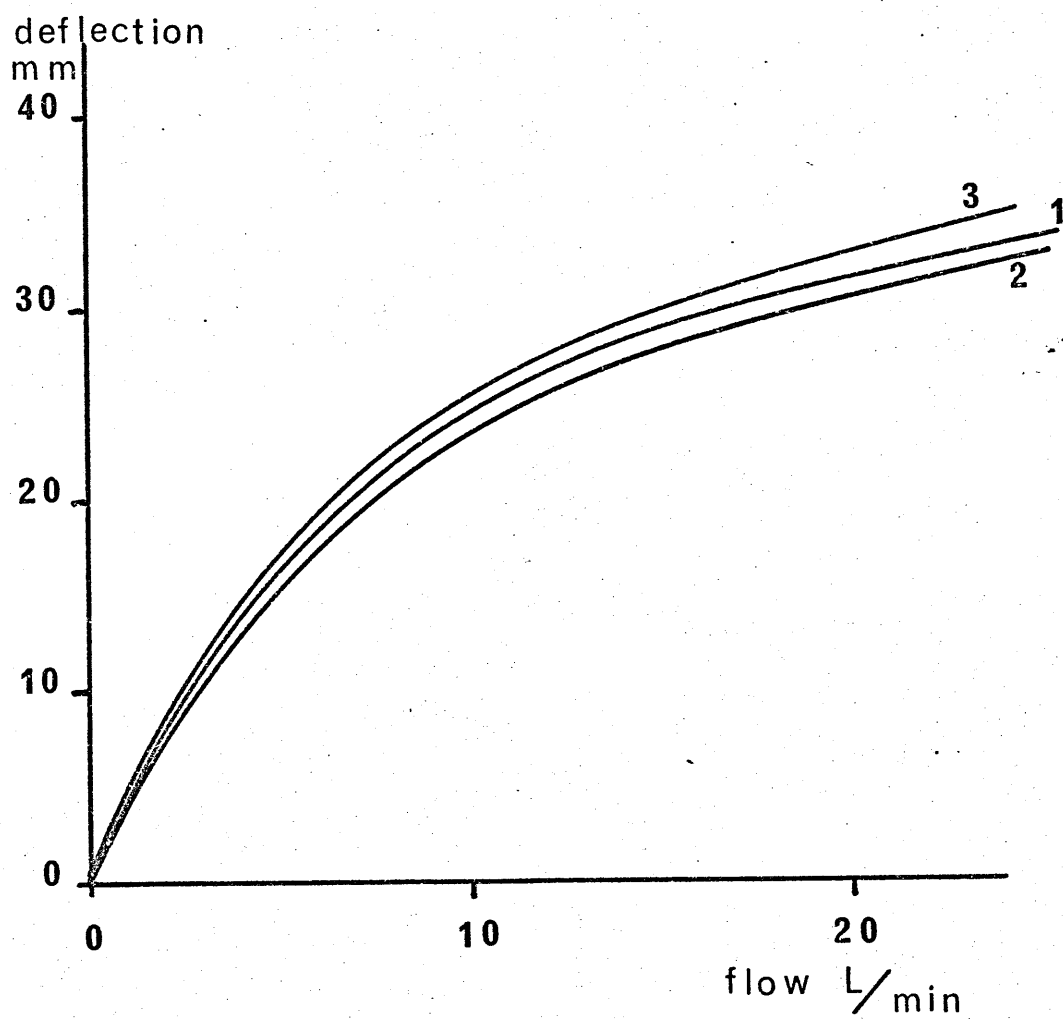


FIG. 2.14

accuracy of $\pm 2\%$ indicated flow $\pm 0.2\%$ full scale reading. The two meters used have ranges 0.5 to 5 and 3 to 25 litres / min.

FIG. 2.12 demonstrates the relationship between the flow through the thermistor head and output reading from the meter on the control box.

Because the signal is then passed to a voltage controlled oscillator, through an analogue to digital converter, a memory and a digital to analogue converter before being applied to the chart recorder input, the voltage applied to the chart recorder input is different to that of the original. A further calibration curve is shown in FIG. 2.13 to demonstrate the relationship between flow and the deflection of the charted airflow trace above zero; for the range settings normally used when supplying charts to speech therapists. This calibration curve is typical but because of the variation in the nominal resistance values of each thermistor a separate calibration curve is required for each head and, strictly, should only be used to quantify data produced by that head. However flow recordings produced by a range of heads vary by only a few percent. FIG. 2.14 shows the variation between three heads. The resistance values of the three thermistors, at 180°C , are as follows :-

$$R_{180}(1) = 1.11 \text{ k } \Omega$$

$$R_{180}(2) = 1.08 \text{ k } \Omega$$

$$R_{180}(3) = 1.17 \text{ k } \Omega$$

It is of course possible to make this response linear but, because the linearisation has to be performed in the anemometer control box, to enable the meter to register a

linear response, this increases the cost of the equipment supplied to the therapist. The results of a large scale field trial will determine whether this is a desirable addition or not.

2.09 HUMIDITY DEPENDENCE.

Because exhaled air is at a relative humidity of about 100% when it passes into the mask, the relationship between the anemometer output for dry and moist air was investigated. The apparatus used was the same as described in 2.08 with the addition of a humidifier (FIG. 2.11(b)). The air from the flowmeter was bubbled through a water-filled flask containing copper gauze discs which was heated to a temperature of 36°C.

An electronic relative humidity meter was placed in the position of the thermistor head to verify that the air at that point was at 100% relative humidity. The anemometer meter readings were taken for various flows. FIG. 2.15 compares this data with the results for dry air from FIG. 2.12. Clearly moistening the air produces no significant change in the anemometer output.

2.10 THE ANEMOMETER RECORDING CIRCUIT.

As stated in 2.03 the frequency response of the cassette recorder precludes direct application of the output of the anemometer bridge. An extension of the anemometer circuit to include a voltage to frequency converter is necessary. The integrated circuit, XRS200, containing a voltage controlled oscillator was used for this purpose. The complete circuit is

effect of dry and moist air
on anemometer output.

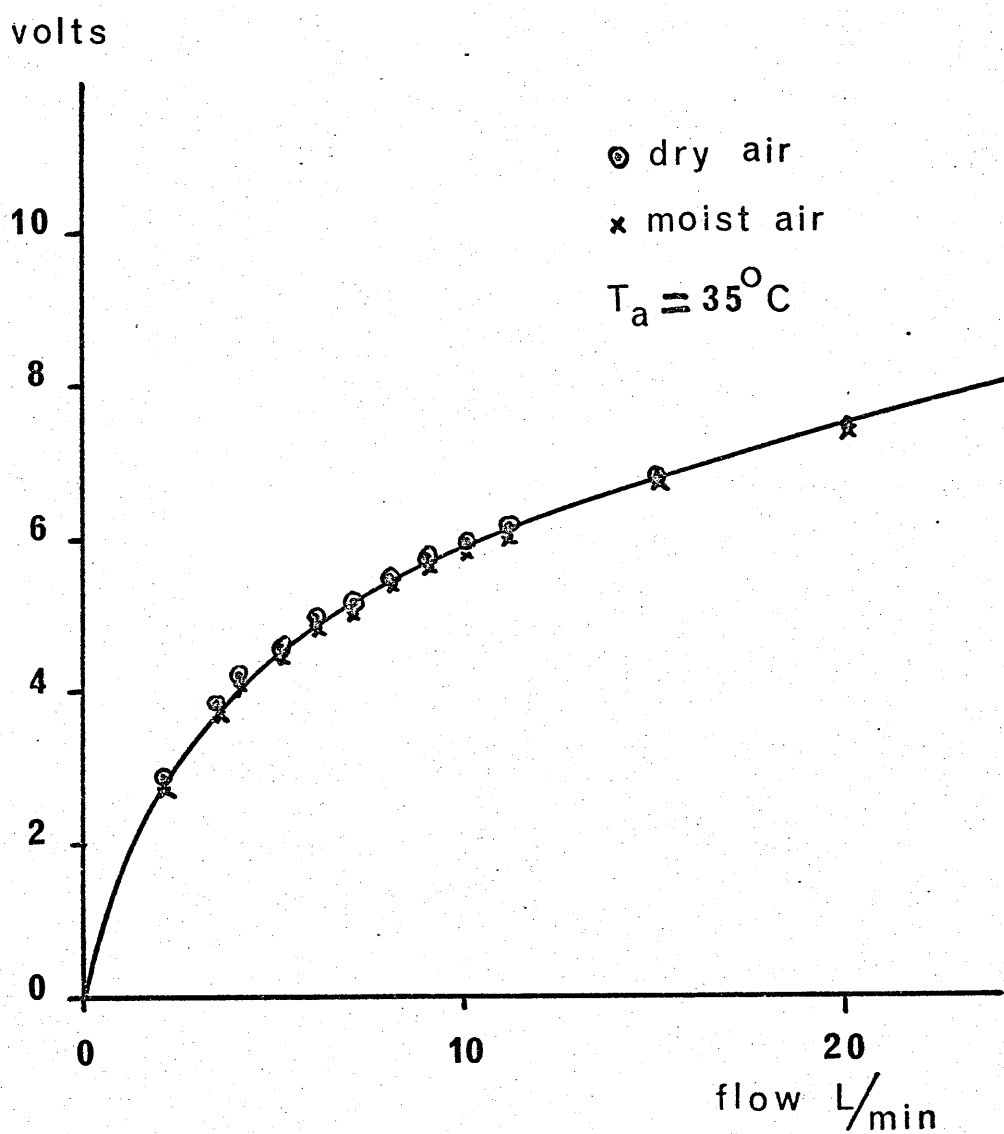
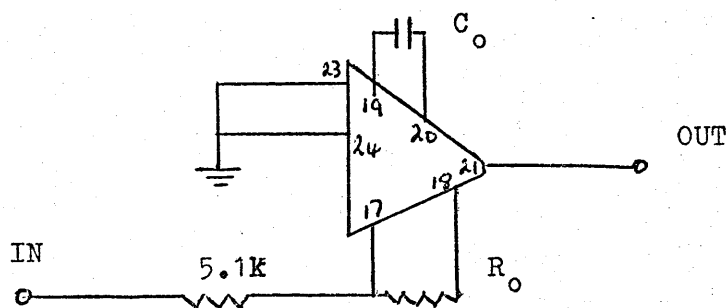


FIG. 2.15

shown in FIG.2.16, the output being adjusted to give a constant amplitude signal over a range of 400Hz to 1kHz corresponding to airflows from zero to 25 Litres/min. The amplitude of the waveform was adjusted to be suitable for direct connection to one channel of the tape recorder.

As shown in FIG.2.16 the XRS200 integrated circuit has two parts. The first part is an amplifier, used here as a unity gain inverter, and the second a voltage controlled oscillator (V.C.O.). The output frequency of this V.C.O. increases with an increasing negative sweep voltage. Because it is convenient for this output frequency to increase with increasing airflow, the output signal from the anemometer circuit is applied to the unity gain inverter to provide the necessary sense input for the V.C.O.

The centre frequency, f_o , of the V.C.O. is determined by the value of the timing capacitor, C_o , indicated in the sketch and calculation below.



$$f_o = \frac{2 \cdot 10^8}{C_o} \text{ Hz}$$

$$= \frac{2 \cdot 10^8}{0.47 \cdot 10^{-6}}$$

$$f_o \approx 400 \text{ Hz.}$$

(where C_o is expressed in pF)

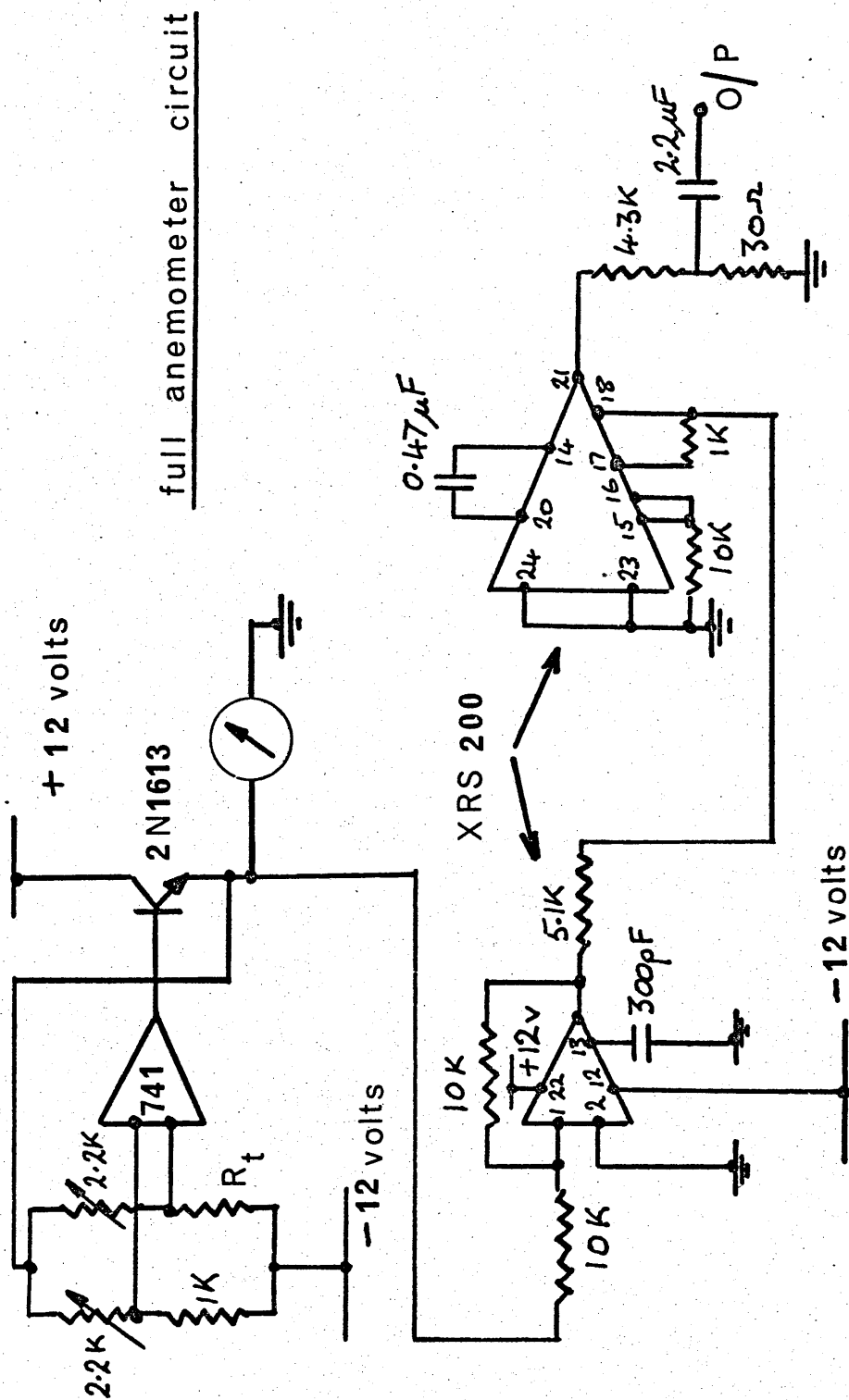
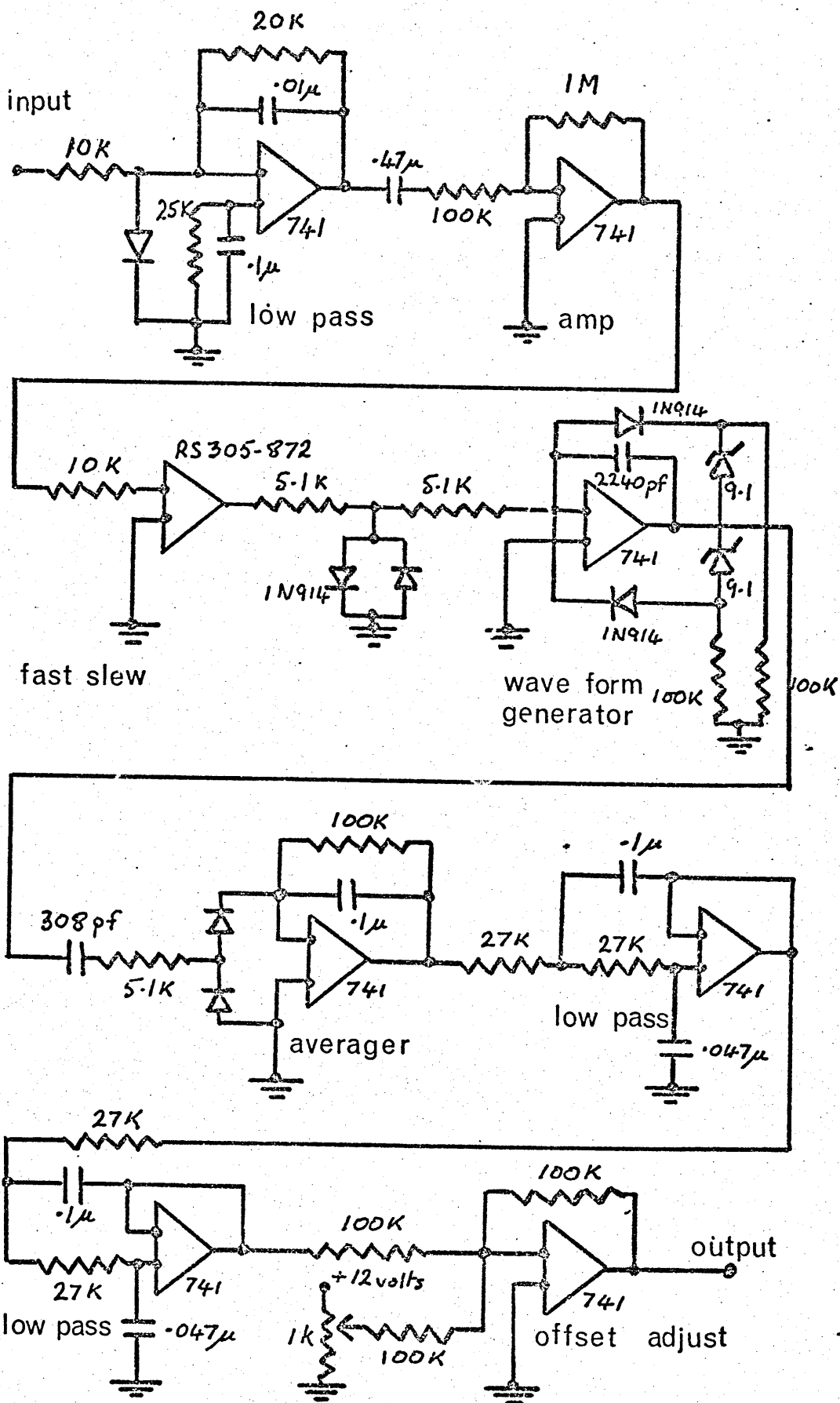


FIG. 2.16



frequency to voltage converter

FIG. 2.17.

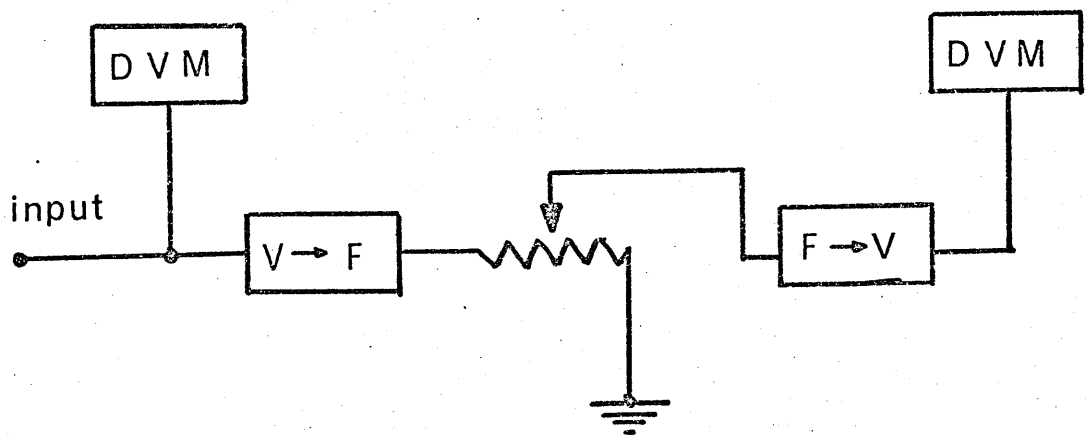


FIG. 2.18

input
volts

linearity of V-F, F-V conversion

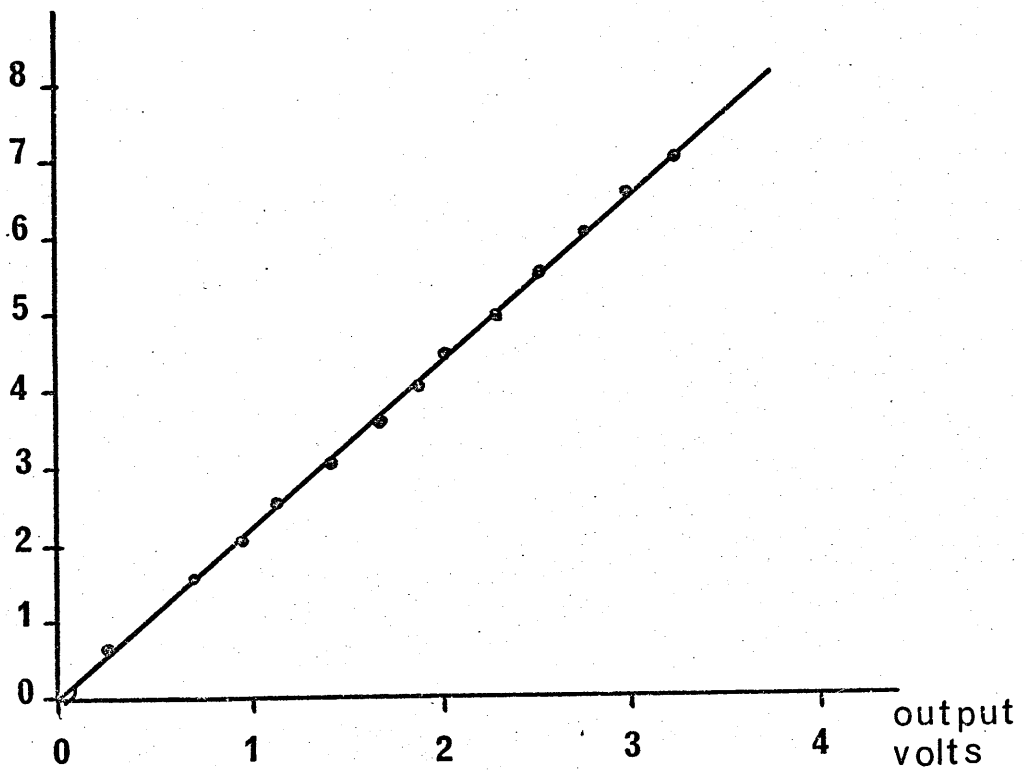


FIG. 2.19

2.11 THE FREQUENCY TO VOLTAGE CONVERTER .

Cassettes received in the processing laboratory are played back on a tape recorder. The airflow signal from this tape recorder has to be recovered in the original voltage form of the anemometer output, ie a frequency to voltage conversion (FIG. 2.17) must be made.

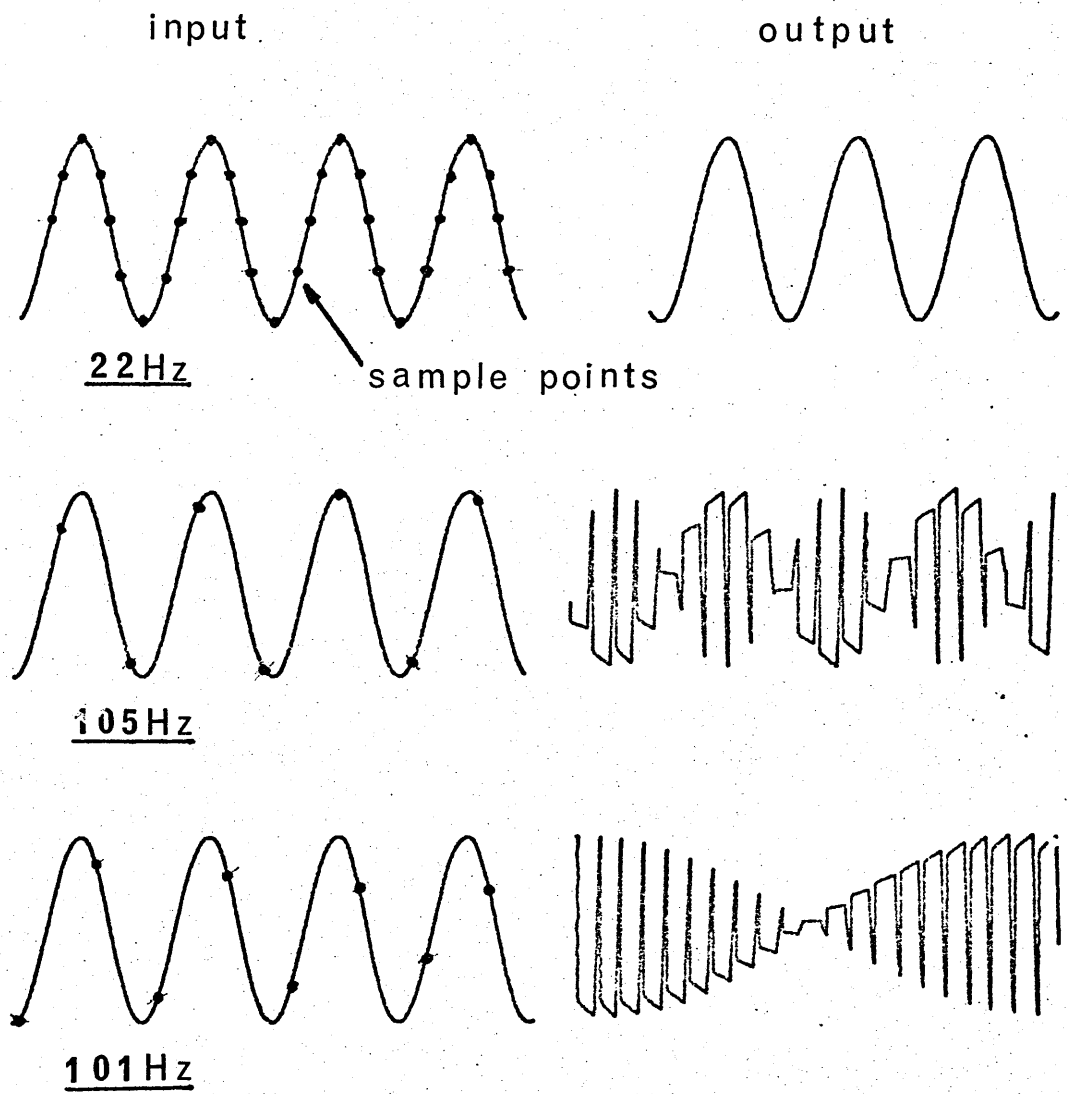
The frequency modulated signal is first filtered to remove tape hiss, then amplified to produce a constant-amplitude signal limited by diodes to ± 1 volt. Integration of this square wave produces a trapezoidal wave which is then averaged producing a voltage output varying with frequency. After filtering to remove any ripple a final unity-gain adder provides offset adjustment.

The linearity of the v - f - v system was checked using the arrangement shown in FIG. 2.18. Input and output readings, plotted in FIG. 2.19, show the linearity.

2.12 THE FREQUENCY DIVIDER.

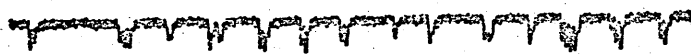
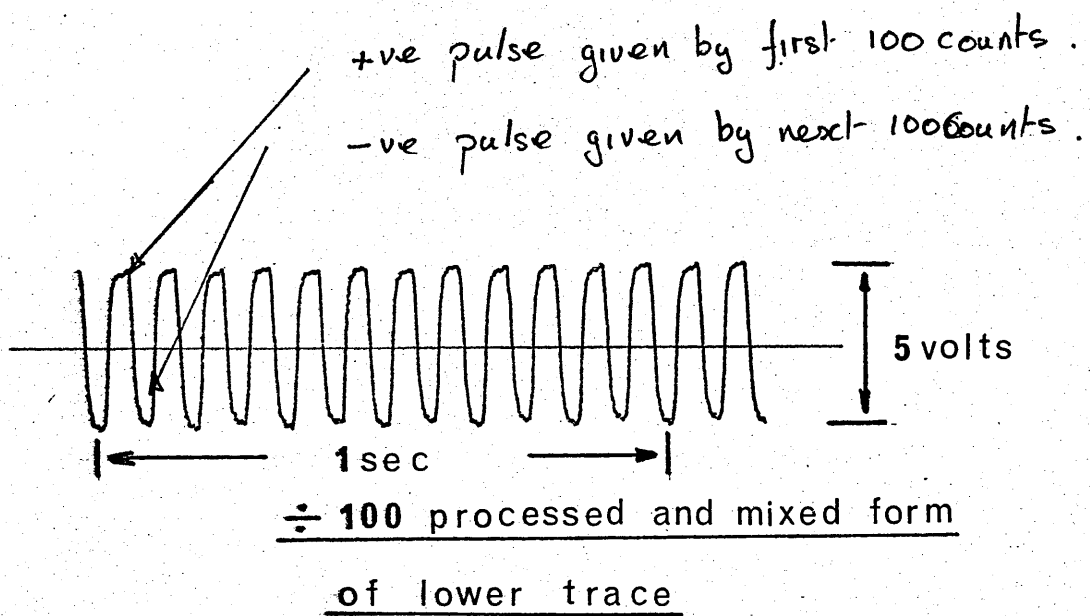
It is easy to distinguish audibly the high frequency voice sounds, such as "s" and "sh", from the background of tape hiss on the recordings. It is, nevertheless, difficult to identify these on chart tracings because the amplitude of these sounds is very close to that of the tape hiss and also because of the aliasing caused by the digitisation and memory storage in the signal processor.

The frequency response of an analogue-to-digital-memory system is dependent on the number of sampling points per cycle available in the memory. The minimum number of sampling



the effect of taking 2000 samples
over 10 secs of 3 different frequencies

FIG. 2.20



2.5 KHz signal applied directly
to the signal processor (.5v. p.t.p.)

FIG. 2.22

points required for faithful reproduction of the input waveform, on reconversion to analogue form, is five per cycle. Fewer sample points per cycle lead to distortion of the output waveform and this effect is termed aliasing. Examples of this distortion are shown in FIG. 2.20.

The memory size of the signal processor used for this work is 4000 words in the single channel mode and 2000 words in the dual channel mode; words 1-3-5 etc being used for channel X and words 2-4-6 etc for channel Y. The frequency response in the dual channel mode for ten seconds recording into the memory is :-

$$\underline{f_r} = \frac{2000}{5} \cdot \frac{1}{10} = \underline{40 \text{ Hz}}$$

As stated in a previous section this can be improved by shortening the periods of recording. Another technique is to divide high input frequencies by 100 to bring them within this response. A circuit designed to accomplish this is shown in FIG. 2.21. The variable trigger level is set to an amplitude just above that of the tape hiss, the Schmitt trigger is then fired by any signals of greater amplitude including the small amplitude "s" and "sh" signals. The Schmitt trigger has a 5 volt logic output suitable for application to the input of a counter which produces from one of its outputs a 5volt logic signal of frequency one hundredth of the input frequency.

The effect of this treatment is shown in FIG. 2.22. The lower trace shows a 2.5 kHz signal directly applied to the signal processor and then relayed to the chart recorder. The upper trace is of the same input signal modified by the frequency divider before application to the signal processor.

CHAPTER THREENASAL ANEMOMETRY RESULTS.3.01 THE CONTROL GROUP: NORMAL SPEECH AND AIRFLOW PATTERNS.

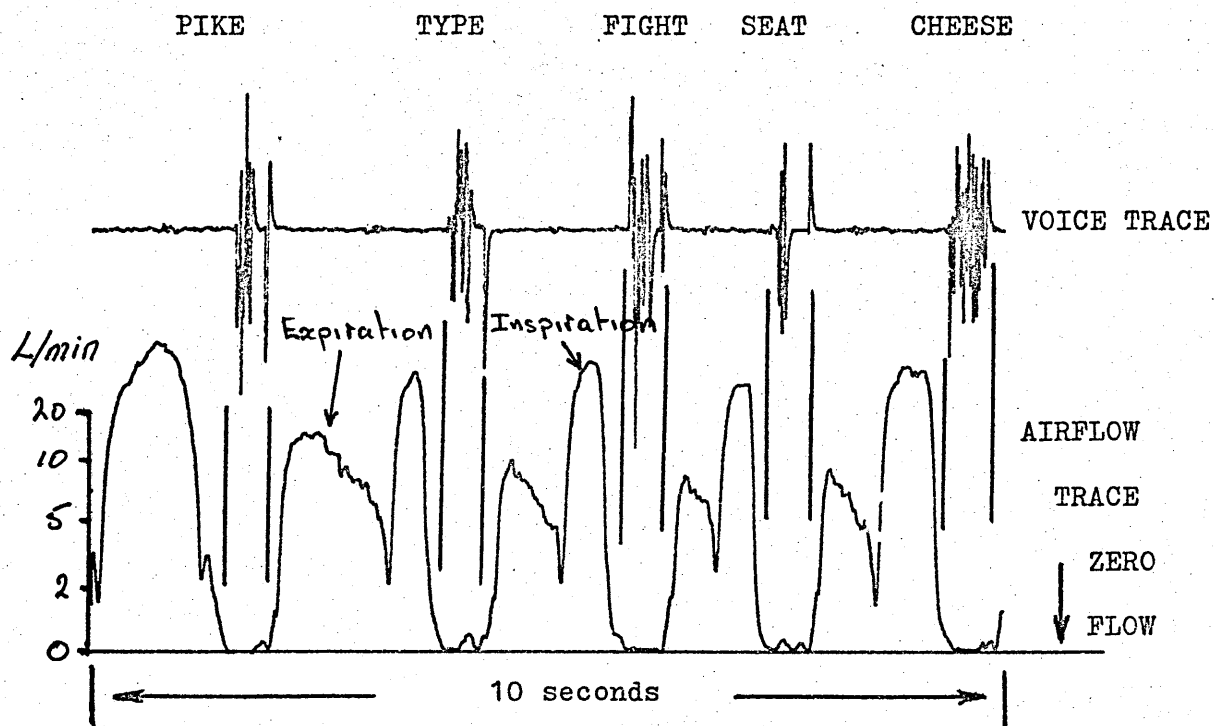
Recordings were made of 100 subjects of all ages, judged to be normal speakers by an expert speech therapist. The resulting charts were examined to establish the patterns of nasal airflow during speech which is accepted as normal for the particular forms of speech in the Exeter area.

A standard word list was used and FIG. 3.1 shows a typical chart of speech and airflow patterns of an adult. The top trace shows the sound record and thus the duration of the spoken words, which are individually identified. The lower trace shows the nasal escape. The horizontal base line is drawn onto the chart to indicate the level of zero flow and the vertical lines are also drawn to identify the beginnings and ends of words.

The airflow patterns, for normal speakers, are different at certain parts of the words, from speaker to speaker and sometimes in the same speaker, but the general overall pattern remains similar to the one in FIG. 3.1.

It is also possible to expand the time scale of the charts and examine in detail each phoneme of a given word as shown in FIG. 3.2.

Short phrases of connected speech can also be recorded and charted but identification of the individual words is difficult unless the words are carefully chosen. (FIG. 3.3)

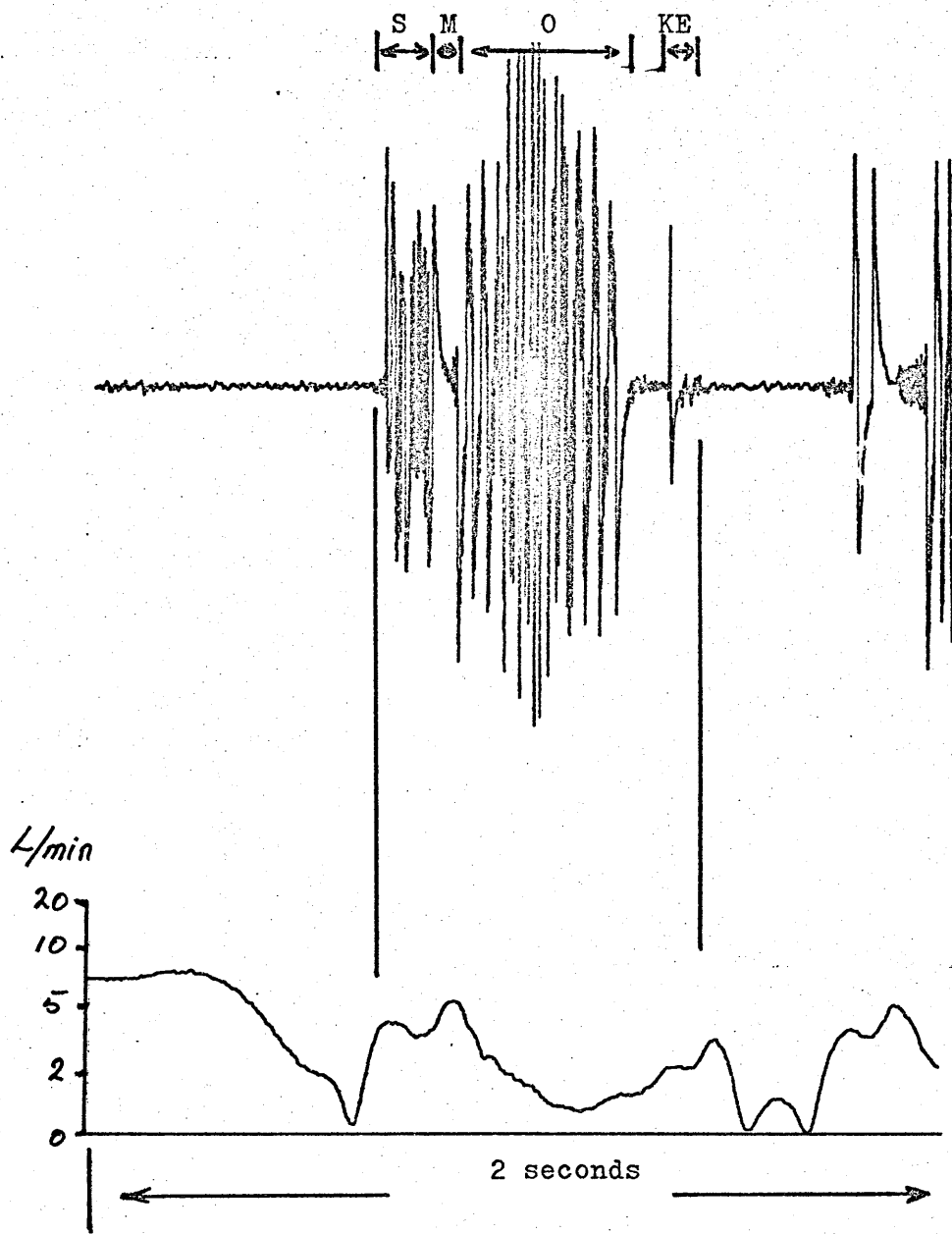


SHOOT SMOKE KING MISSING NUMBER

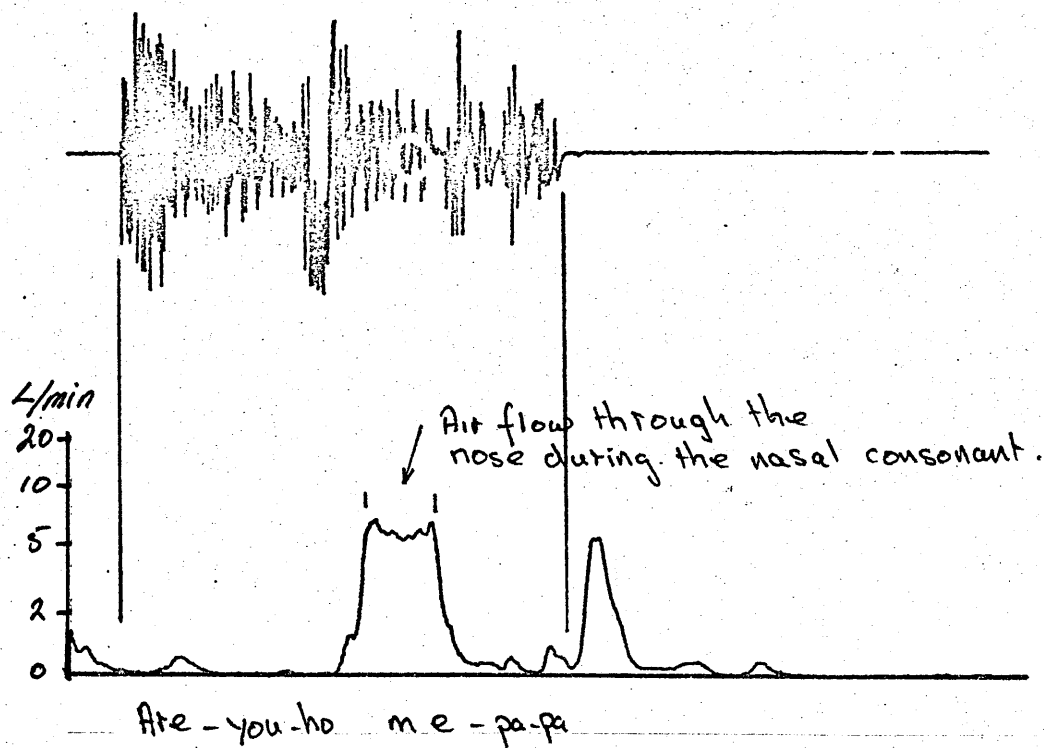


Speech and airflow patterns of a normal adult

FIG. 3.1



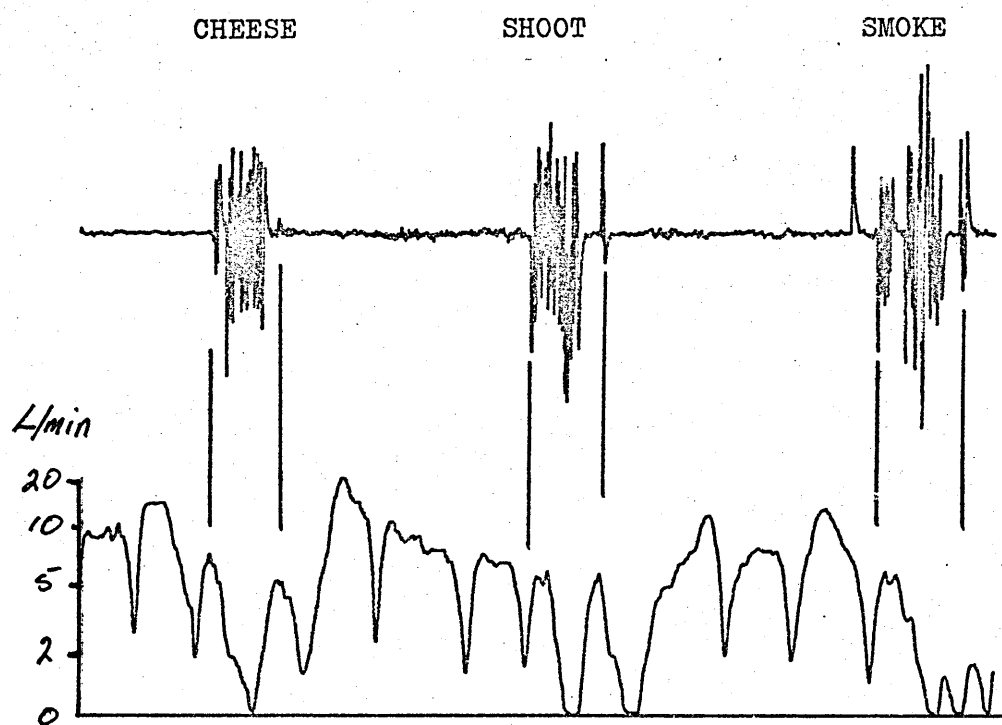
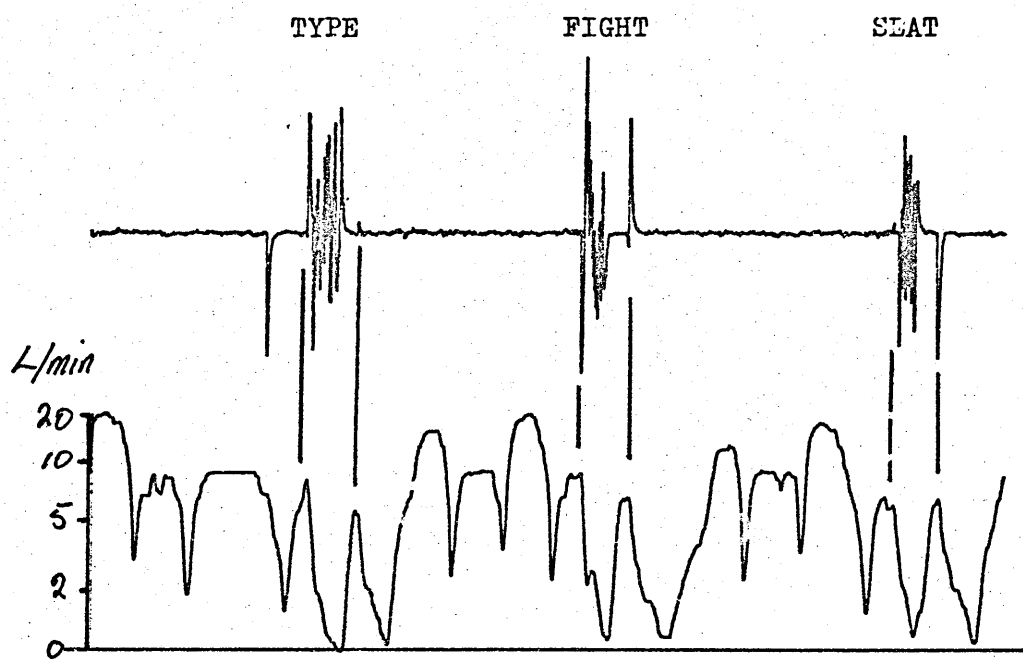
Expanded speech and airflow pattern (hypernasal).



Nasal anemometer trace of the phrase;

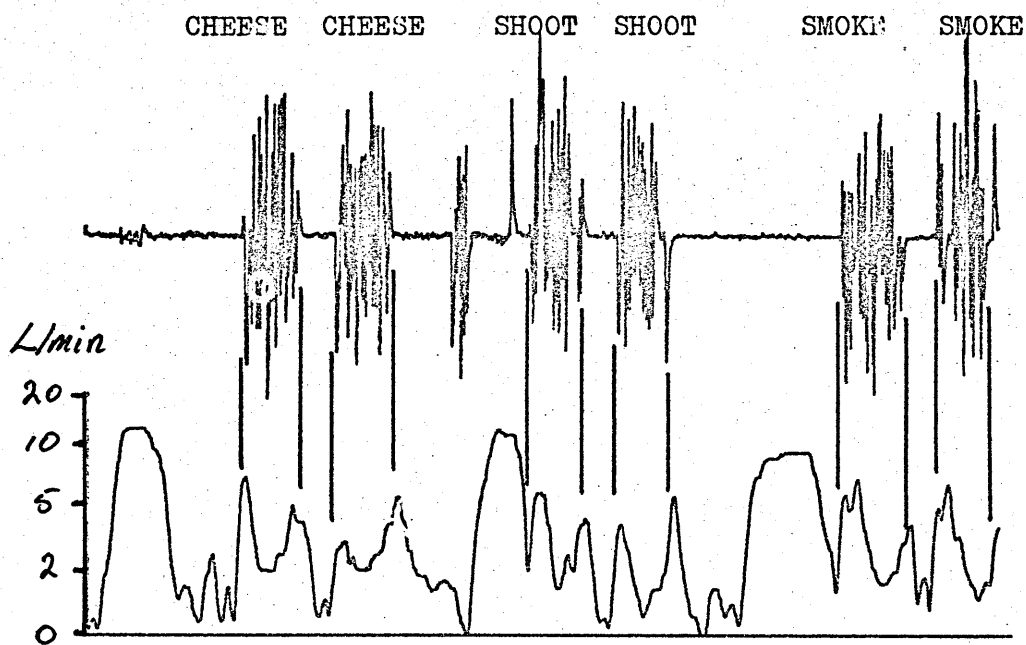
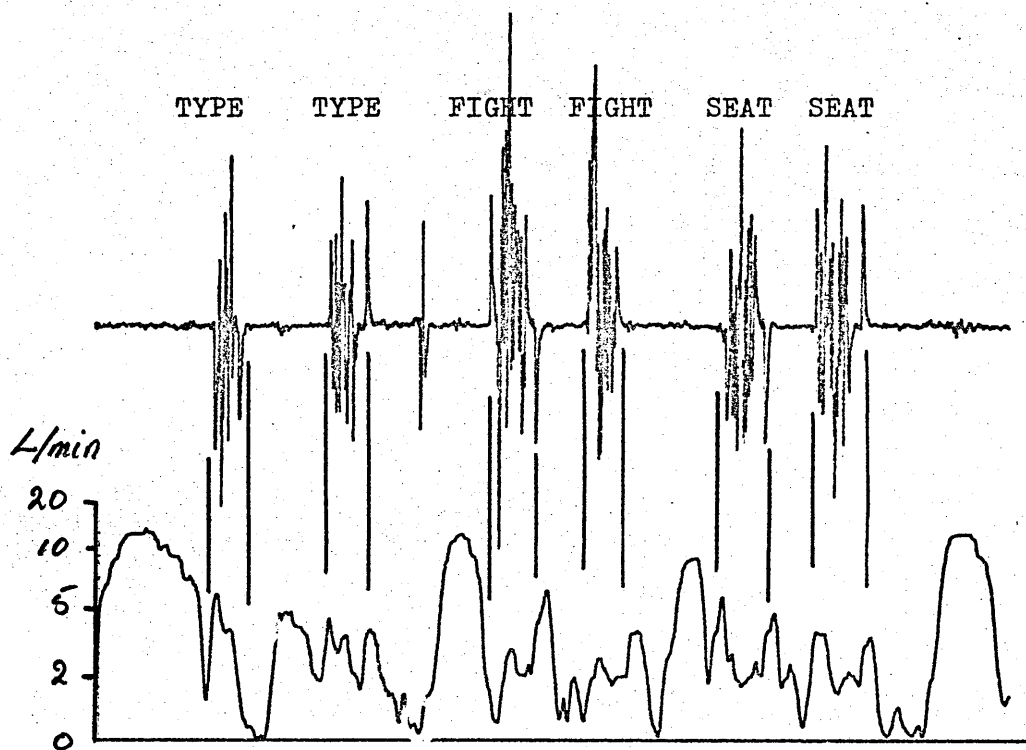
" are you home Pa Pa " spoken by a
normal adult.

FIG. 3.3

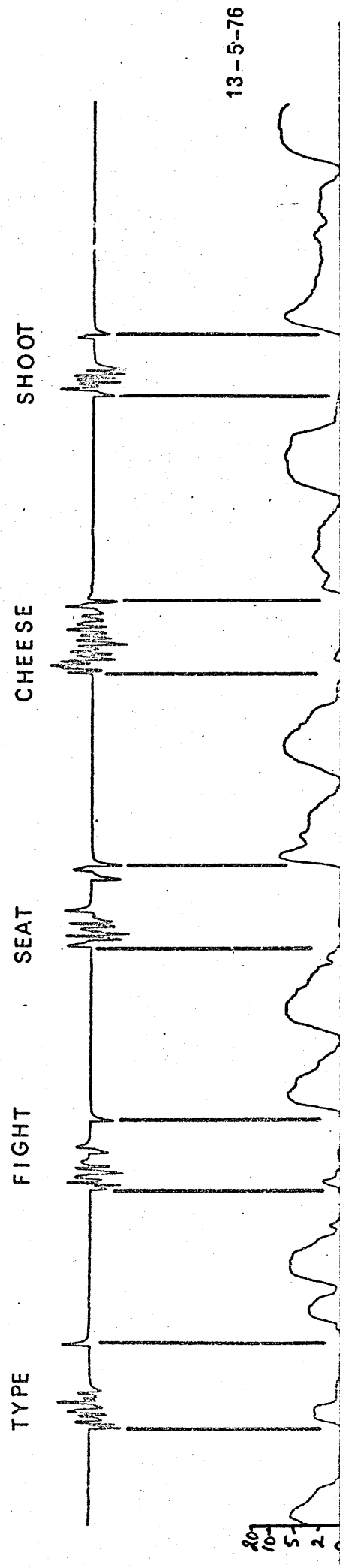
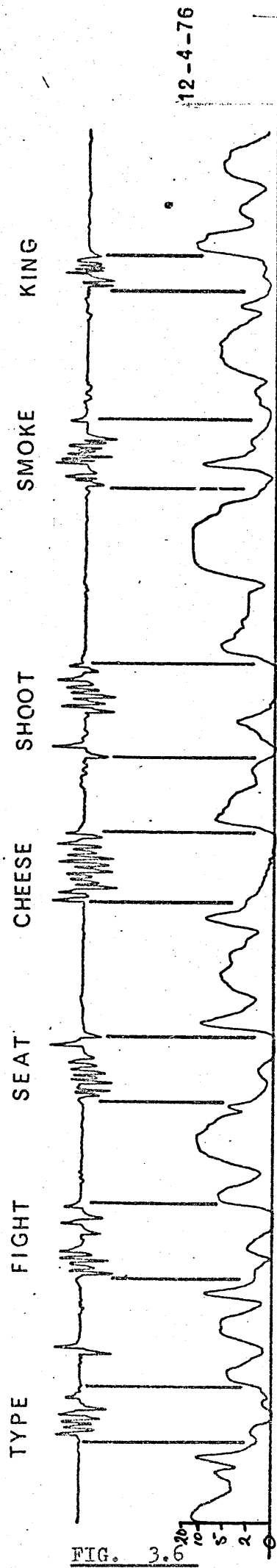
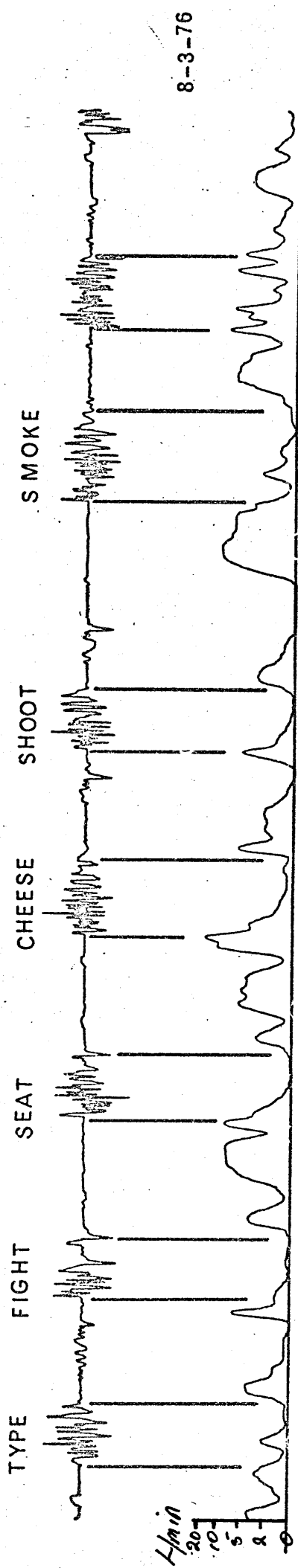


Speech and airflow patterns of a hypernasal patient.

FIG. 3.4



Speech and airflow patterns of a hypernasal patient.



3.02 ABNORMAL SPEECH AND AIRFLOW PATTERNS.

Charts from typical hypernasal patients are shown in FIG. 3.4, which demonstrates speech with gross nasal escape when pressure is built up in the mouth, FIG. 3.5 shows a general escape occurring at all times during speech. FIG. 3.6 demonstrates how the anemometer has been used to record the progress of a patient under treatment with a Palatal Training Appliance and Visual Aid. (Tudor and Selley,(1974) and Ellis and Selley,(1973)).

CHAPTER FOUR.DISCUSSION OF THE USE OF THE NASAL ANEMOMETER.4.01 RESULTS OBTAINED AND THEIR VALUE.

To the time of writing this thesis approximately 100 patients have been monitored by the author and many more by speech therapists. A large scale field survey by speech therapists using a further seven nasal anemometers is being undertaken to make assessments of patient's nasal escape before, during and after various regimes of treatment. The anemometer charts thus produced are attached to a patient's hospital record to monitor improvement during treatment. Three of these anemometers are in use in major plastic surgery units to assess the success of operative treatment of cleft palate.

Having said this it must be remembered that the nasal anemometer tells the clinician nothing about the intelligibility and quality of the patient's speech and in the final analysis this has to be a subjective assessment.

Speech therapists using the equipment in their clinics have reported no problems in operation and many have found other uses for the anemometer; for example, to monitor escape of air from the side of a patient's mouth during utterance of a lateral "s". This is done by removing the rubber mask and holding the flow tube to the patient's lips.

Some difficulties have been encountered in the fitting of the mask over the patient's nose. If the rubber cushion is too close to the nares the airflow is restricted and a false anemometer reading is obtained. This is overcome by applying a simple test before recording. The patient is asked to breathe gently through the nose while the speech therapist watches the

meter on the control box for an adequate airflow reading. This normally is 5 to 10 Volts depending on the size of the patient. The patient is asked to vocalise some nasal consonants and again a check is made of airflow reading. If the mask cannot be adjusted to give an appropriate airflow reading the undernose piece must be used.

It is necessary for the patient, using the anemometer, to keep his head still during recording as movement of the flow tube produces artifact on the airflow trace.

It is also necessary to have quiet surroundings for recording and preferably a sound proofed room should be used. Any ambient noise, or interjection by the therapist, makes it difficult to exactly identify the beginning and end of individual words uttered by the patient. With very young patients, or those with poor eyesight, it may be necessary to give a prompt before each word, but this does not give a charting problem if there is a second of silence between words. During processing, words are identified by listening to the recording and it is therefore possible to identify which words are spoken by the therapist and which by the patient. The use of a voice trigger to identify the beginning and end of individual words was constructed but was found not to be ideal as the speech therapist preferred to have some idea of phrasing from the appearance of the trace.

The size and weight of these early devices has made them difficult to transport from one clinic to another. At the time of writing attempts are being made to reduce the size and weight by constructing a battery-operated anemometer with a multiplexed output to a small single-track tape-recorder.

Preliminary trials with a prototype device have been encouraging.

4.02 PROCESSING CAPABILITIES AND COSTING.

For the apparatus to become generally used by speech therapists the cost of each chart must be reasonable: ie it must compare with the cost of processing a pathological specimen. This is governed by the number of charts that can be produced by the processing equipment.

At the time of writing there ^{are} eight anemometers in use and these each produce an average of five recordings per week. Each chart takes 30 minutes to prepare and, given a 30 hour working week for the equipment, this gives a capability for 60 charts per week. Even with the present, below capacity, working load a cost per chart of £4 to £5 would sensibly amortise the equipment and processing costs. This compares favourably with the cost of a pathological specimen or Xray. For example in Exeter the average cost of chemicals and film is £ 7 to £ 11, at the time of writing.

CHAPTER FIVEAPPARATUS FOR USE IN THE EARLY DIAGNOSIS OF DYSFUNCTION OF THE
OROPHARYNGEAL MUSCULATURE.5.01 INTRODUCTION.

As stated in Chapter One, research by the Exeter group has, probably for the first time, produced an effective form of treatment for certain cases of dysarthria. During the course of this work, it became clear that poor muscular coordination - see below - may have existed in some cases since birth. Accordingly it was thought worthwhile to investigate from birth onwards to see whether early signs of poor coordination may be demonstrated. The possibility of devising an early corrective treatment can then be investigated.

The musculature used in sucking, swallowing and respiration is the first to come under voluntary control. Much of the same musculature is used for speech so a great deal may be learned from an investigation of the mechanisms of sucking, swallowing and respiration. Establishment of normal patterns can then be followed by studies to identify abnormal behaviour.

The following part of this thesis describes attempts to develop simple, easily-applied techniques which will provide the earliest indication of abnormal soft palate, tongue and pharyngeal muscle movement without the use of X-ray techniques. By studying the normal rhythm and necessary coordination of sucking, swallowing and respiration in infants during bottle feeding it is hoped that very early signs of abnormality may be detected and attempts made to link these with the prolonged feeding times and excessive nasal regurgitation which appear,

from the records of patients treated, to be among the early signs of hypernasality.

5.02 THE NORMAL PROCESS OF DEGLUTITION.

The normal process of neonatal feeding from a bottle takes place in several stages:-

- (1) The pressure in the mouth is reduced by a combination of tongue action and a lowering of the mandible. This causes milk to flow from the bottle into the mouth.
- (2) Voluntary muscular contraction of the tongue and cheeks throws the bolus backwards onto the post-pharyngeal wall. This region of the pharynx has high sensory innervation from the glossopharyngeal nerves, where local nerve endings and those of the soft palate and epiglottis are stimulated.
- (3) The soft palate is elevated against the post-pharyngeal wall to close off the nasal cavity. The epiglottis moves to guard the laryngeal opening, until the bolus reaches the oesophagus which simultaneously opens to receive it. Aspiration of the food into the larynx is prevented by an associated reflex apnoea (arrest of respiration).
- (4) The bolus is then propelled along the oesophagus by peristaltic waves in the muscles of the oesophageal walls.

Detailed anatomical studies of these processes have been made by Blockley and Miller (1971), Logan and Bosma (1967) Bosma (1957) and Payne and Olsen (1974).

Logan and Bosma state :- " In the normal infant the separate actions of suckle, swallow and respiration occur

in a patterned sequence under medullary control. These recur rhythmically in these patterns during established suckle feeding. Suckle movements generally precede and appear to facilitate swallow action, which in turn inhibits respiration."

Further reference to Ardren et al (1958) and Peiper (1963) reinforce this view.

Blockley and Miller discuss the necessary ability of the posterior portion of the infant's tongue to seal against the soft palate thus preventing air entering the mouth from the naso-pharynx during sucking. They also discuss the importance of correct oral movement during feeding for later speech development.

5 .03 DISCUSSION OF THE MEASUREMENTS TO BE MADE AND METHODS.

It was decided to monitor simultaneously the pressure in the mouth, the passage of the bolus over the closed larynx and epiglottis and the arrest in respiration during this cycle.

If graphs showing the time sequences of these can be obtained and their relative positions for normal feeding established, then it should be possible to identify any abnormal pattern. The following is a brief discussion of some possible methods for making such observations together with more detailed descriptions of those finally selected.

a) SUCK.

The pressure in the mouth was measured by a National Semiconductors pressure transducer connected to the oral cavity by a catheter of 1 mm. internal diameter and 1m. of

silicone rubber tubing. To prevent occlusion of the catheter by the 'biting' action, which accompanies suckle, a special teat was designed to allow a metered supply of milk and to protect the suction catheter. A system was designed to provide a standardised milk supply from a reasonably constant head, so giving, to each infant studied, the same set of parameters for obtaining milk.

b) SWALLOW.

Three methods of monitoring the passage of the bolus were considered. The first using ultrasonic doppler techniques was ruled out on safety grounds. Wells (1973) has suggested that a doppler detector, operating at an intensity of less than 40 mW/cm^2 may be used without time restriction. He also comments, however, that the anatomical site of irradiation can be very important. Since the area of application was very close to the developing spinal chord and since the measurement was not for the benefit of the patient it was felt that even a small risk was not justified. The ultrasonic generator available produced 18.2 mW/cm^2 , according to the manufacturer's data. This is very close to the lower limit of some positive biological effects on nervous tissue according to Wells' data. (His Fig. 1) The second technique, described by Payne and Olsen (1974), uses a sensitive strain gauge connected to a short piece of silastic tube fastened around the neck of the patient. For similar ethical reasons this method was also rejected.

The adopted technique used a sensitive microphone, applied to the side of the patient's neck, to listen to the passage of the bolus.

c) RESPIRATION.

Initially, a commercially available apnoea-monitor was used to monitor respiration. This device, in

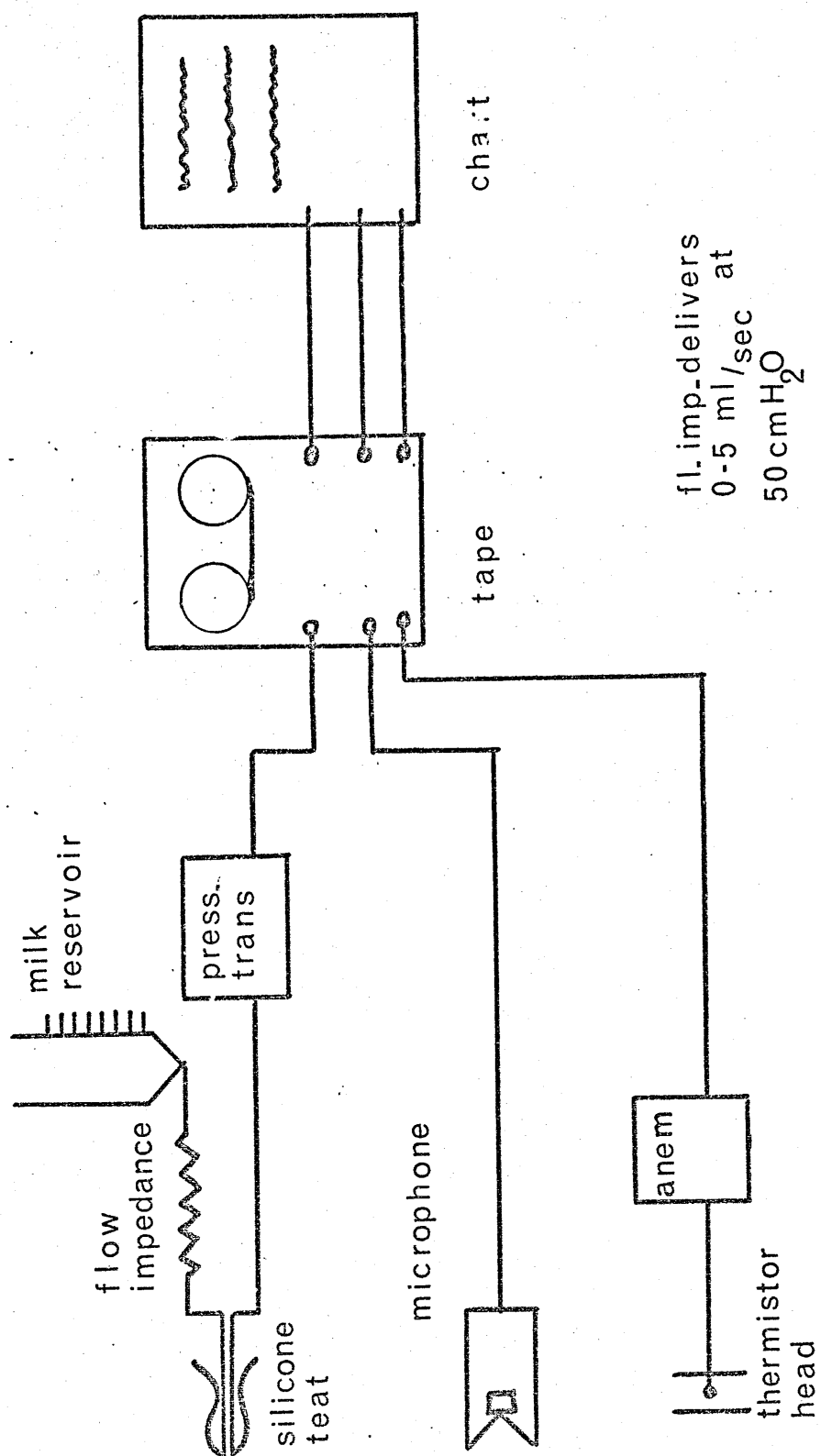


FIG. 5.1

schematic of the apparatus for monitoring oral function

general use in the special-care baby unit, employed changes in the electrical impedance of the thorax to register inspiration and expiration phases. However on analysing the first series of recordings it became clear that, although capable of measuring respiration rate and arrest, the commencement of air flow through the nose and larynx did not coincide with the change of signal from the apnoea-monitor.

Other equipments tested for the monitoring of respiration included several types of belt pneumograph. Two of these, the air filled tube with pressure transducer and the conductive foam transducer, are described in later sections. These were not used in full scale clinical trials either because of difficulties in fitting to neonates or because they were not considered safe, for example, because of the pressure exerted on the infant's thorax.

The method used eventually for the final clinical trials incorporated a miniature version of the nasal anemometer previously discussed. A thermistor, mounted in a small anemometer head, was placed just beneath one nostril of the subject. This was considered safe as it allowed free passage of air through the sensing head and the second nostril was not occluded.

A schematic representation of the apparatus for these measurements is shown in FIG. 5.1 . One channel of a four-track instrumentation recorder accepted the amplitude-modulated signal from a throat microphone; the other three were frequency-modulated. Charts were made using either an S.E. Labs, U.V. light-writer or the processing and charting equipment

described for nasal anemometry.

The details of the equipments developed to monitor sucking, swallowing and respiration patterns are described in the following sections. Details are also given of the methods used to verify the respiration monitor artifact and the techniques tested for respiration monitoring, not used in clinical trials.

5.04 and 5.05 The apparatus for monitoring intra-oral pressure.

5.06 The throat microphone.

5.07 Impedance pneumography.

5.08 The balloon pneumograph.

5.09 The conductive foam pneumograph.

5.10 The anemometer respiration monitor.

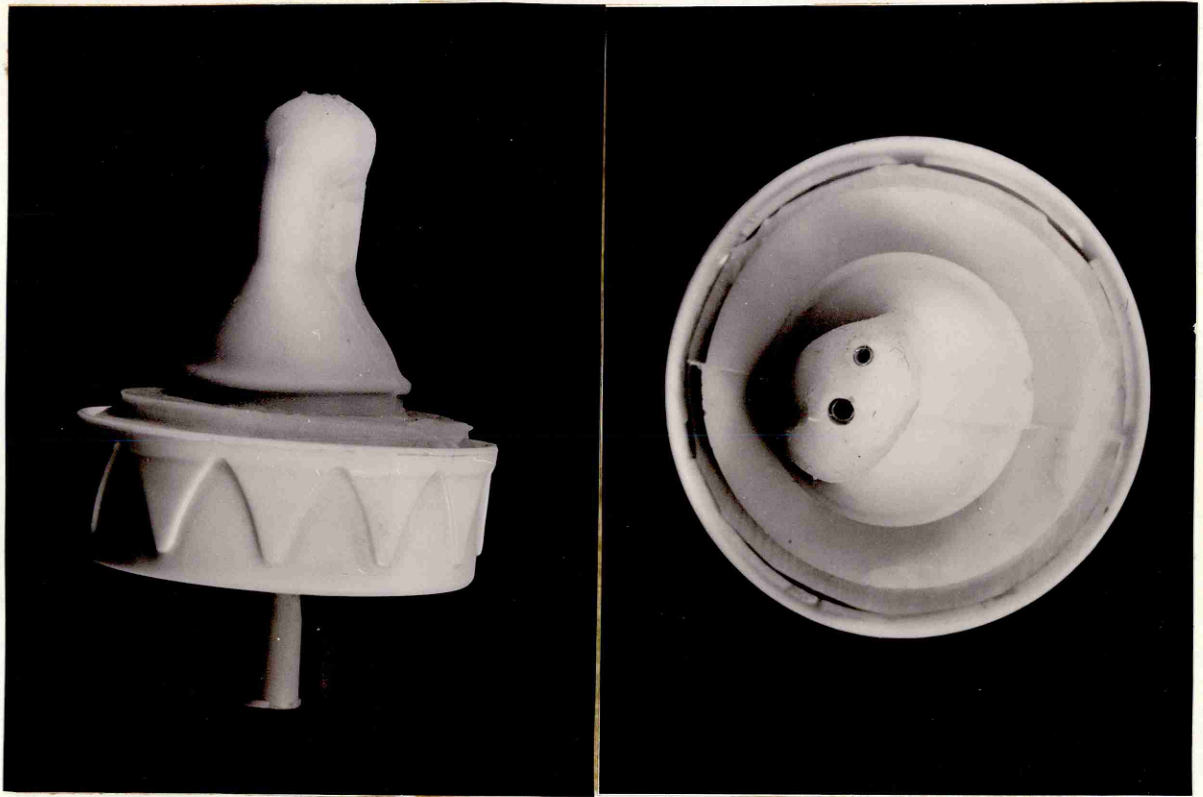
5.04 APPARATUS FOR THE SUPPLY OF MILK AND INTRAORAL

PRESSURE MEASUREMENT.

a) CONSTRUCTION OF THE TEAT.

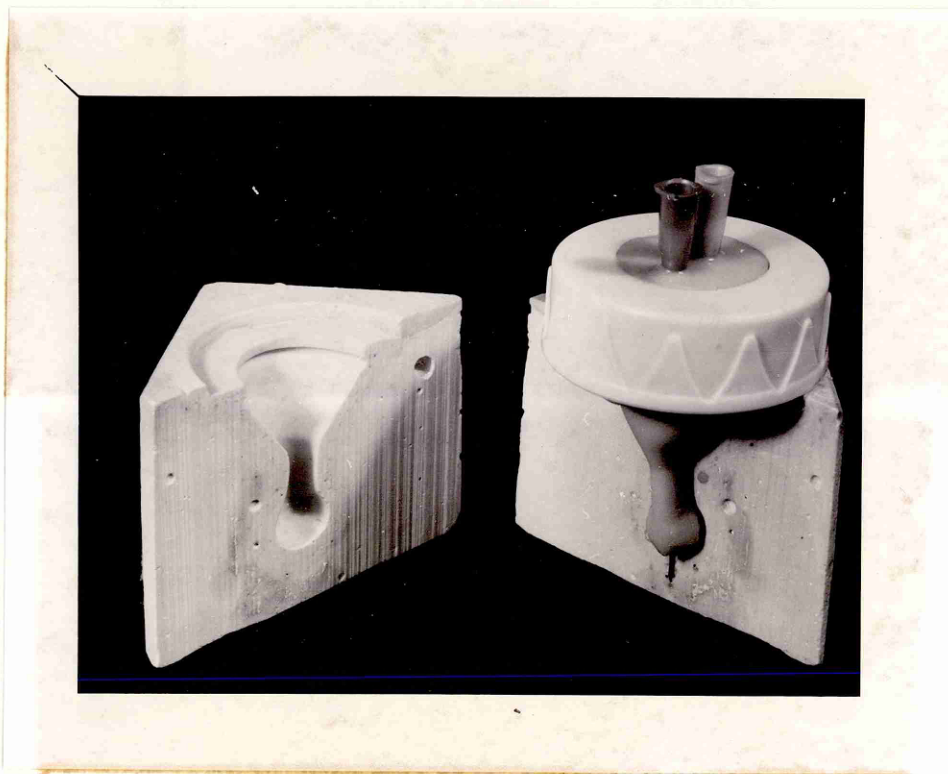
The teat was cast from medical grade silicone rubber as this material can be easily sterilised by autoclave. The shape of the teat was that of a normal feeding teat when 'bitten' by the infant. This flattened shape was necessary as a circular section would hold the mouth open and create swallowing difficulties. Two standard 1.5 mm. bore suction catheters 35 mm. long, were cast into the teat so that their ends were flush with the end of the teat and as near to the position of the normal milk exit as possible. (FIG 5.2(a))

The casting of this silicone teat was simplified



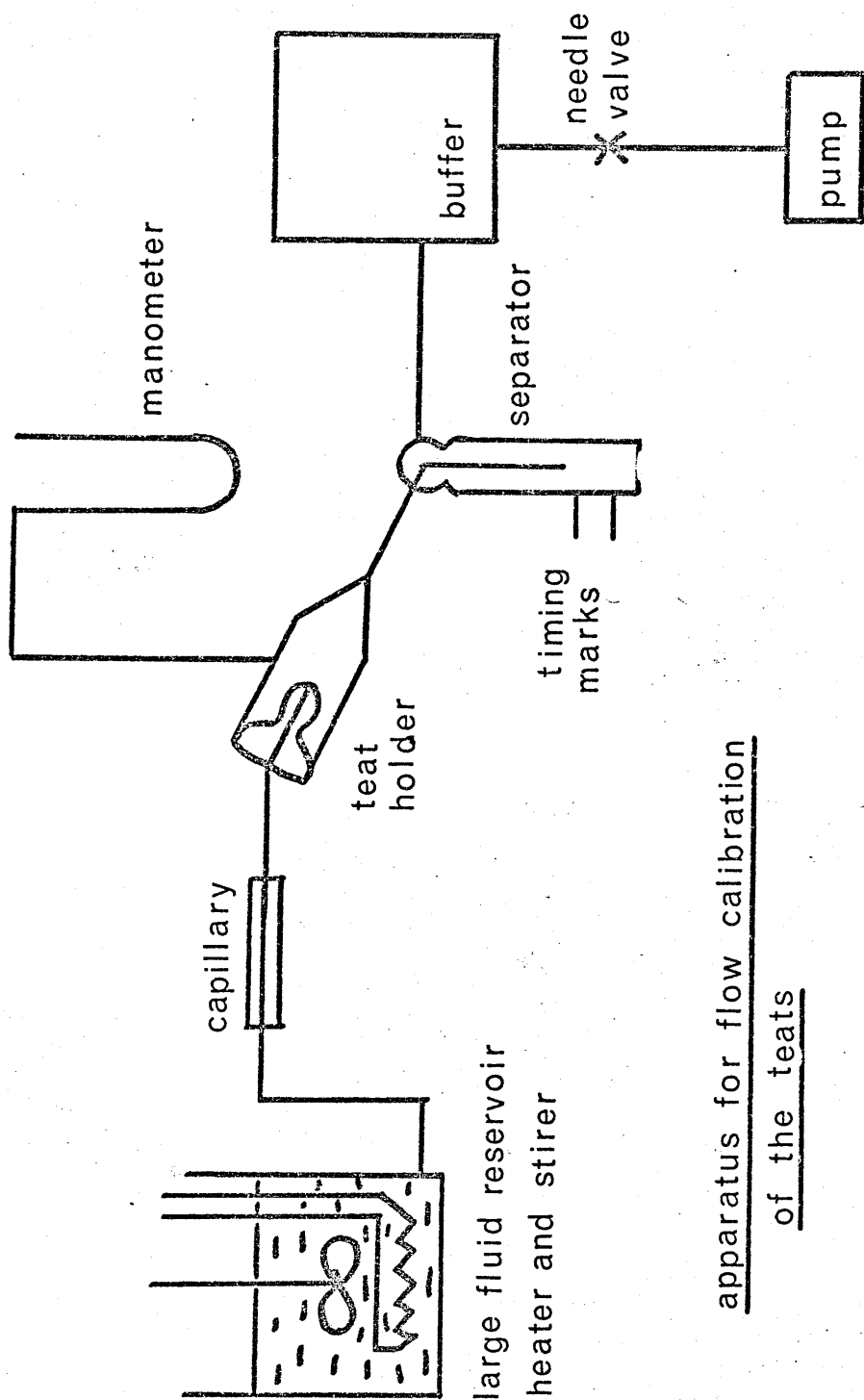
THE SILICONE TEAT.

FIG. 5.2(a)



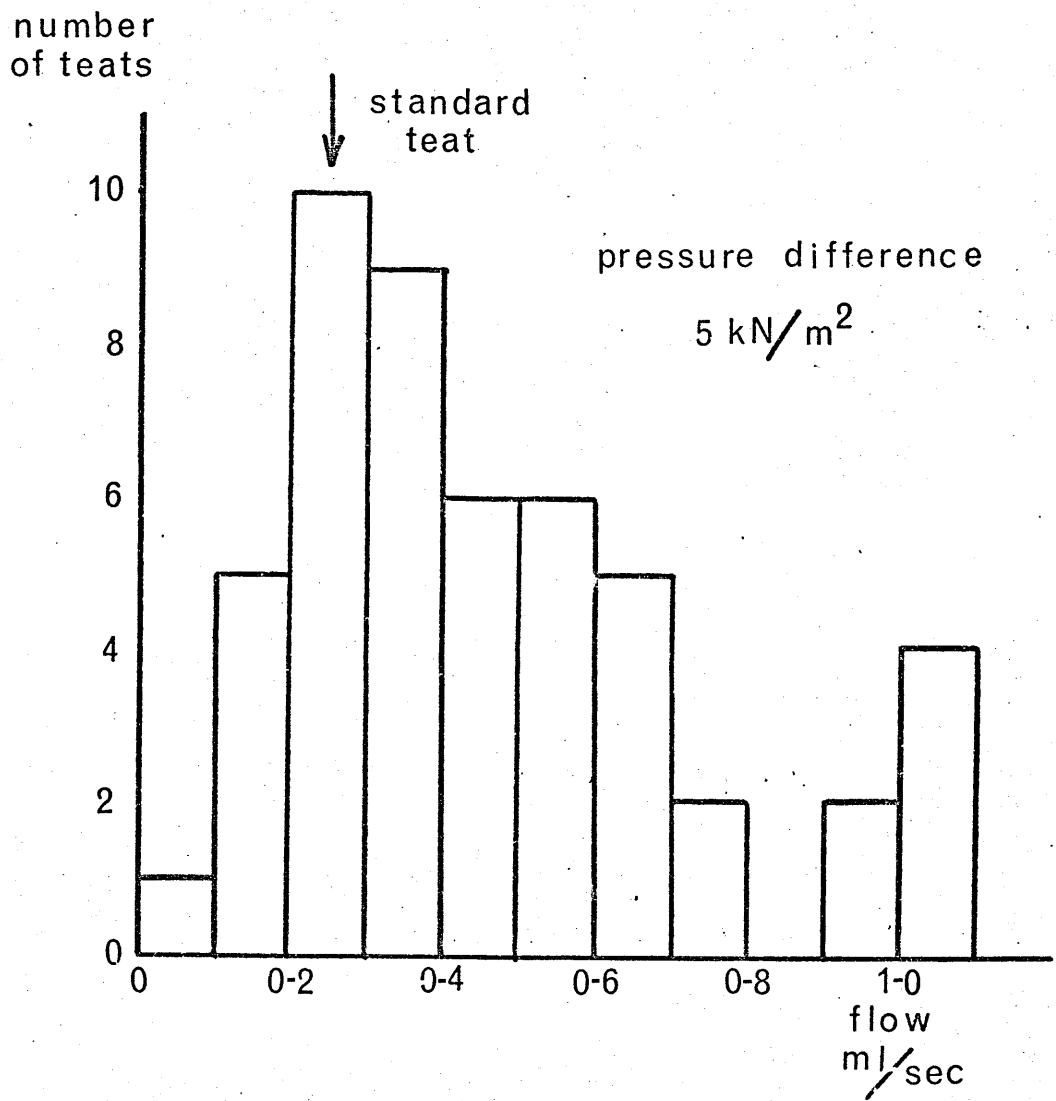
THE TEAT MOULD.

FIG. 5.2(b)



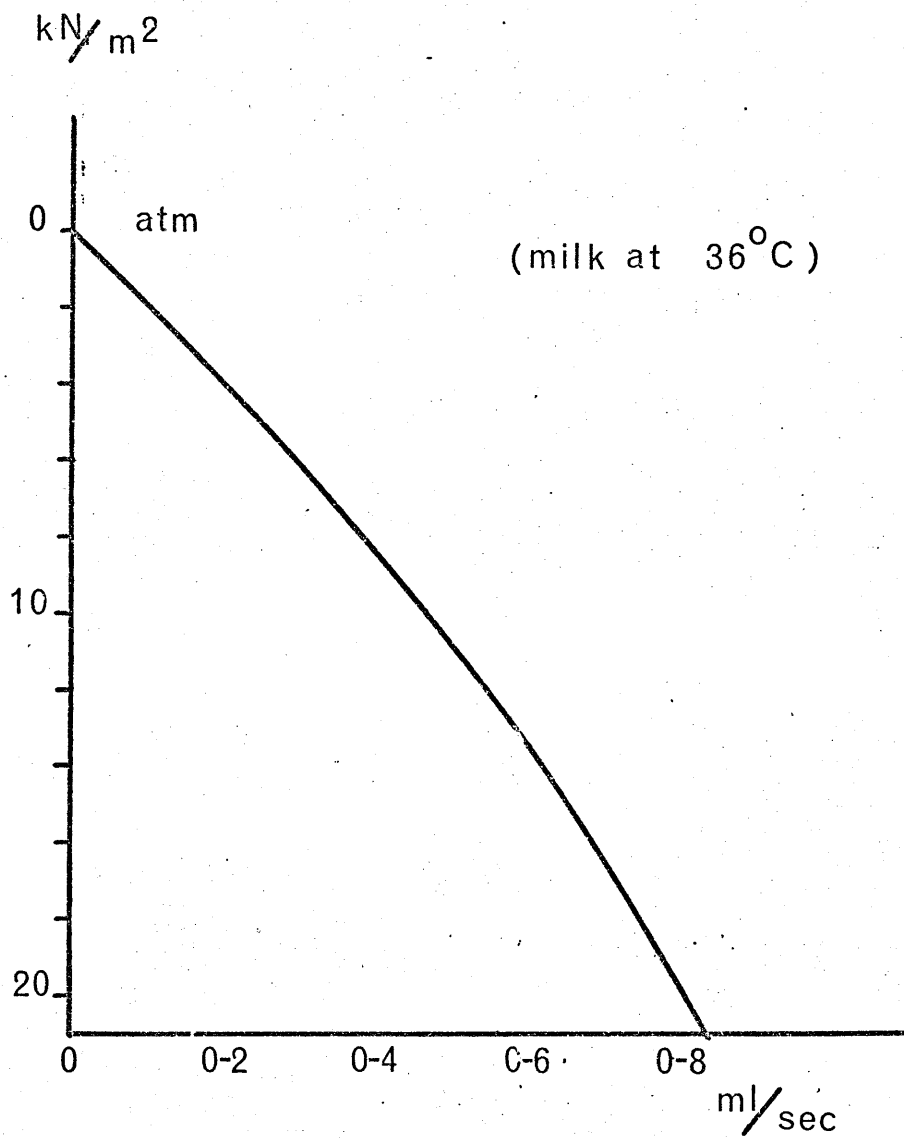
apparatus for flow calibration
of the teats

FIG. 5.3



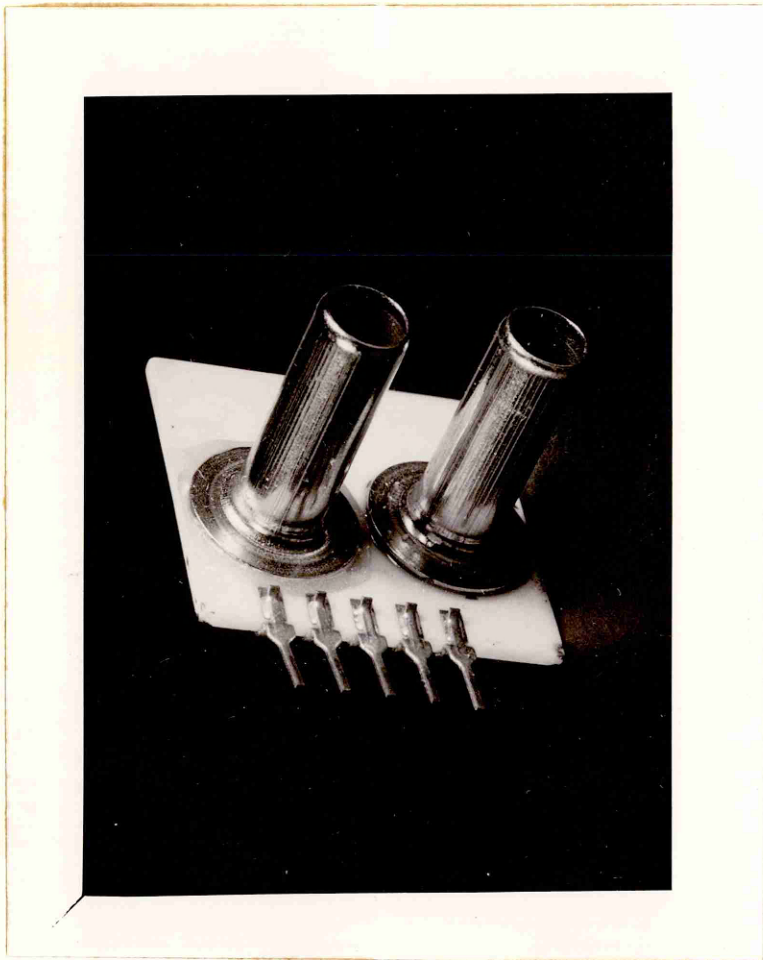
histogram of flow for 50 teats

FIG. 5.4



flow / pressure difference for
standard teat

FIG. 5.5



THE LX1602A PRESSURE TRANSDUCER.

by the use of a split mould made by a dental technician from artificial stone. A commercially available rubber teat was filled with wax and formed to the required shape. This was then used as a pattern, giving a very smooth finish to the interior of the mould. (FIG.5.2(b))

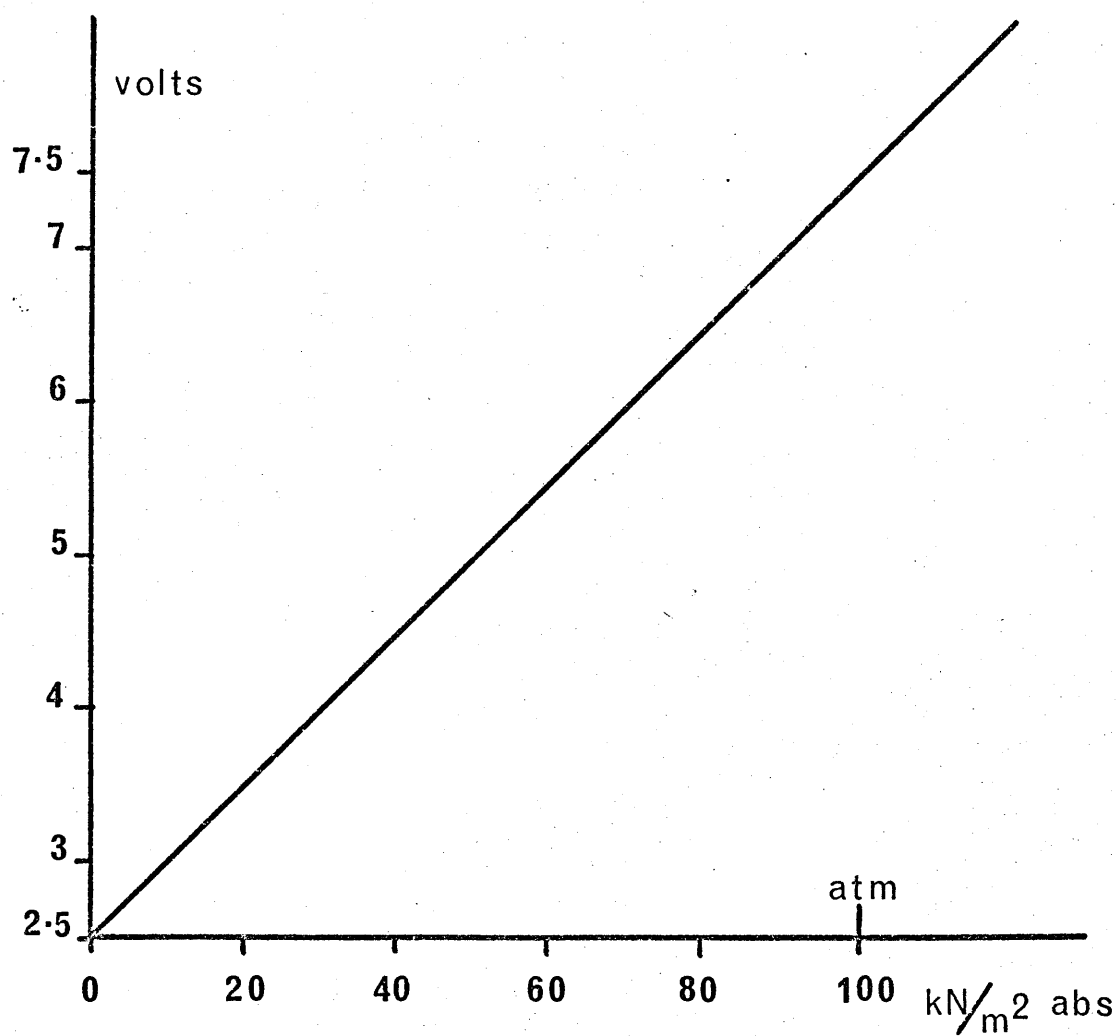
b) THE MILK SUPPLY.

The pressure vs. flow characteristics of fifty commercial rubber teats were measured using the very simple apparatus sketched in FIG. 5.3. A histogram of the flows at one selected pressure difference shows that there is a fairly uniform distribution across a wide range of flows.(FIG. 5.4)

For experimental purposes, where a constant behaviour was required, a standard teat was developed. The standard teat was constructed to deliver 0.25 ml/sec, of milk at 36 °C, at a pressure difference of 5 kN/m². (That is when the pressure in the infant's mouth, at the end of the teat, is at 96 kN/m².) This was achieved by introducing a glass capillary, 50 mm. long and 0.5 mm.bore,into the milk supply tube between the teat and the milk reservoir. The pressure difference vs. flow characteristics of this device are shown in FIG. 5.5.

c) THE PRESSURE TRANSDUCER AND ASSOCIATED CIRCUITRY

A N.S. LX1602 A absolute pressure transducer was used, this is shown in FIG.5.6. The working principle of the device is a vacuum referenced diaphragm which flexes with applied pressure, this flexure being monitored by a piezo resistive sensor. The main advantage of this device is that it only requires a stabilised voltage supply of 10 to 30 volts d.c., the output



output voltage / pressure for
NS LX1602 D transducer

FIG. 5.7

voltage from the built - in signal conditioner and linear integrated circuit is linearly proportional to the applied pressure. The pressure vs. output voltage characteristic is shown in FIG.5.7.

The pressure produced in the mouth, during sucking, for an infant, is within the range 101 to 85 kN/m², (a conversion from kN/m² to cm H₂O is shown in Appendix 1.) thus only a small portion of the range of the transducer is used and external amplification of the voltage output is required. Because the device is vacuum referenced its output voltage at atmospheric pressure is 7.5 volts, which ,for the present purpose, it is convenient to offset to zero.

The maximum change in this output voltage produced by a sucking infant is ;

$$\Delta V_{(max)} = (V_a - V_o) \frac{P_{s(max)}}{P_a}$$

where :- V_a = the output voltage at atmospheric pressure.

V_o = the output voltage at zero pressure.

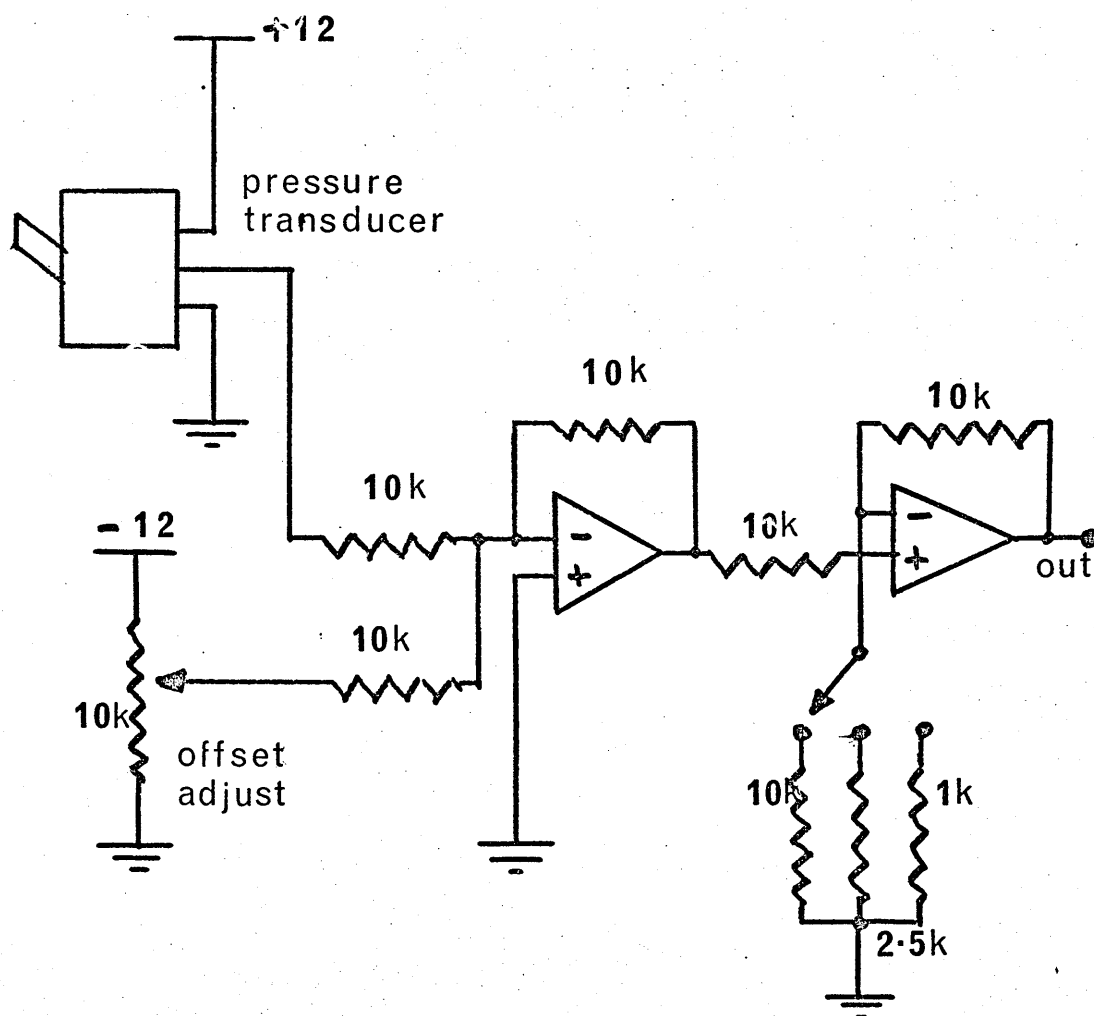
$P_{s(max)}$ = the maximum change in pressure achieved by a sucking infant. N/m²

P_a = atmospheric pressure. N/m²

$$\Delta V_{(max)} = (7.5 - 2.5) \frac{16325}{101325}$$

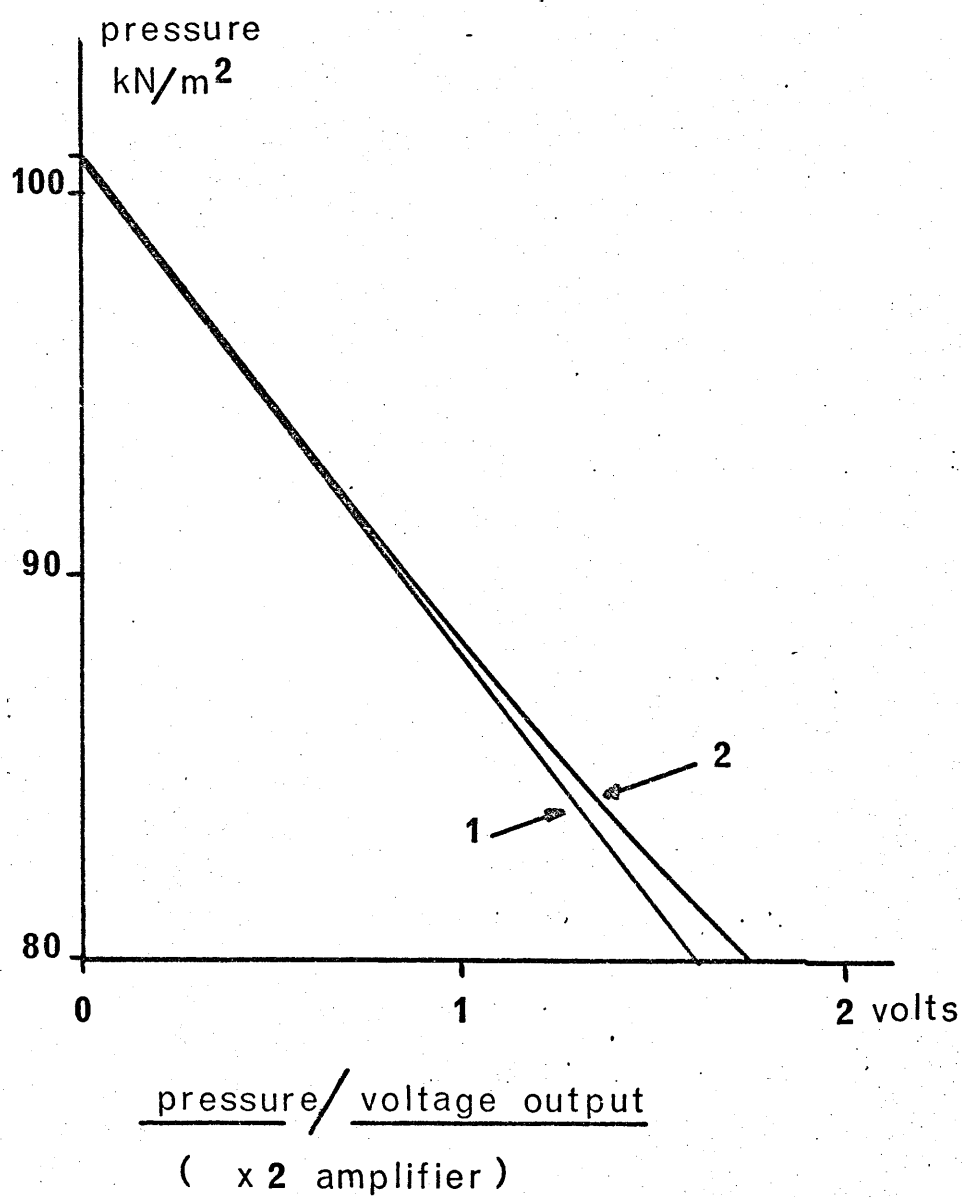
$$\Delta V_{(max)} = 0.80 \text{ volts}$$

but this is offset by 6.70 volts .



offsetting circuit for the pressure transducer

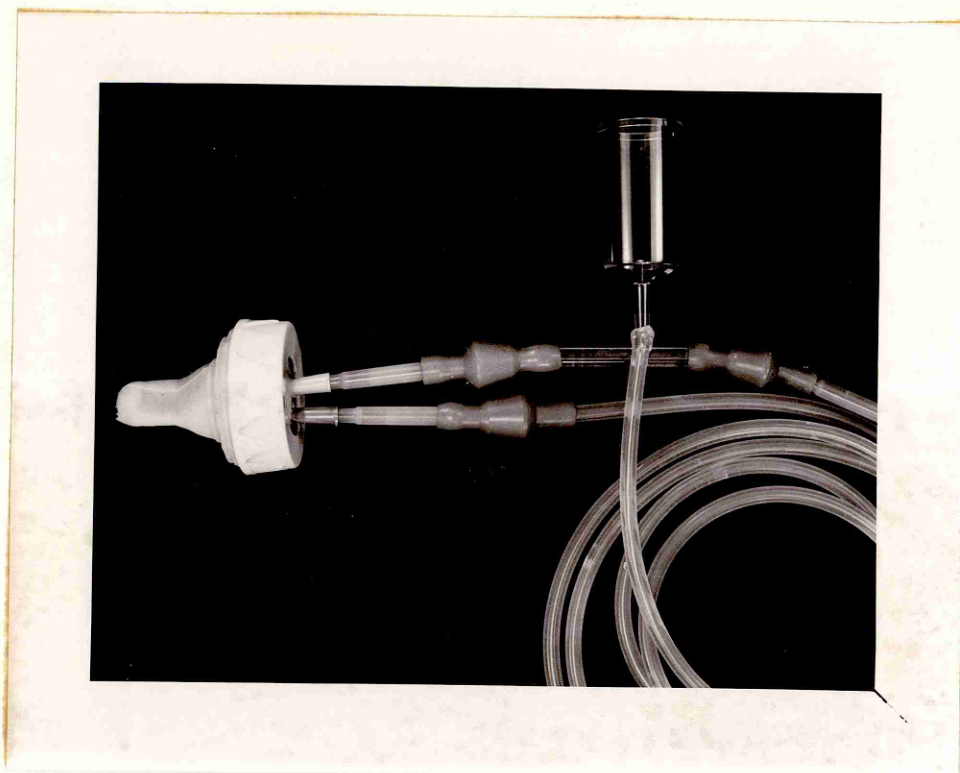
FIG. 5.8



1 manufacturers data

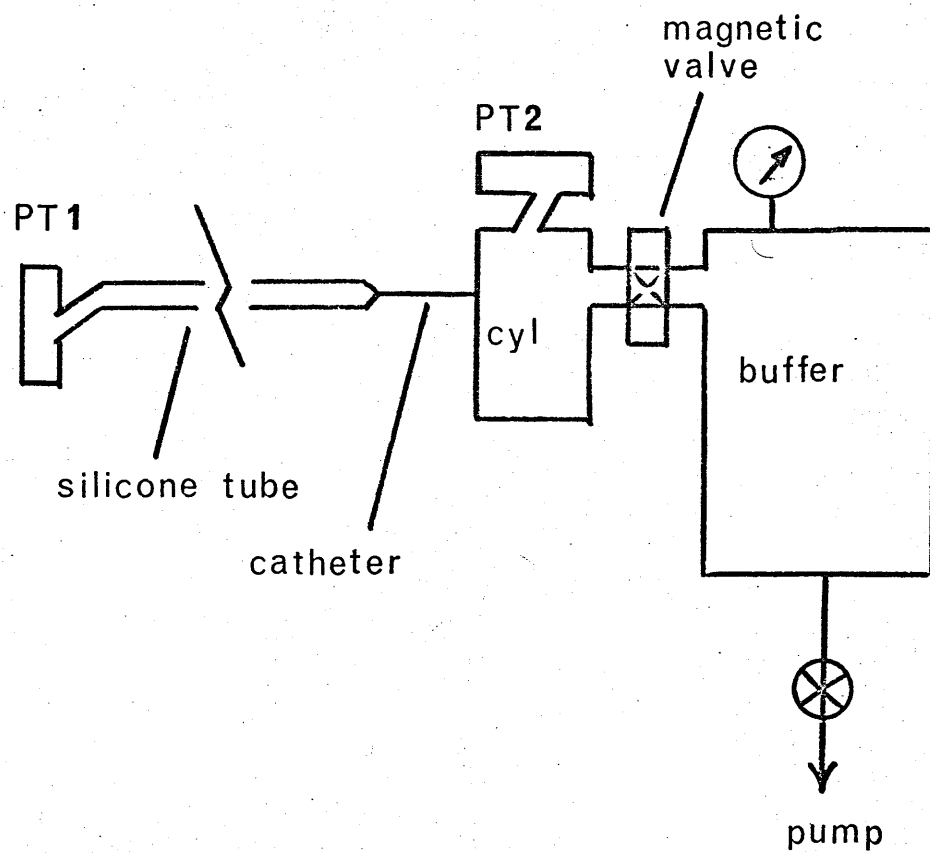
2 U tube manometer calibration

FIG. 5.9



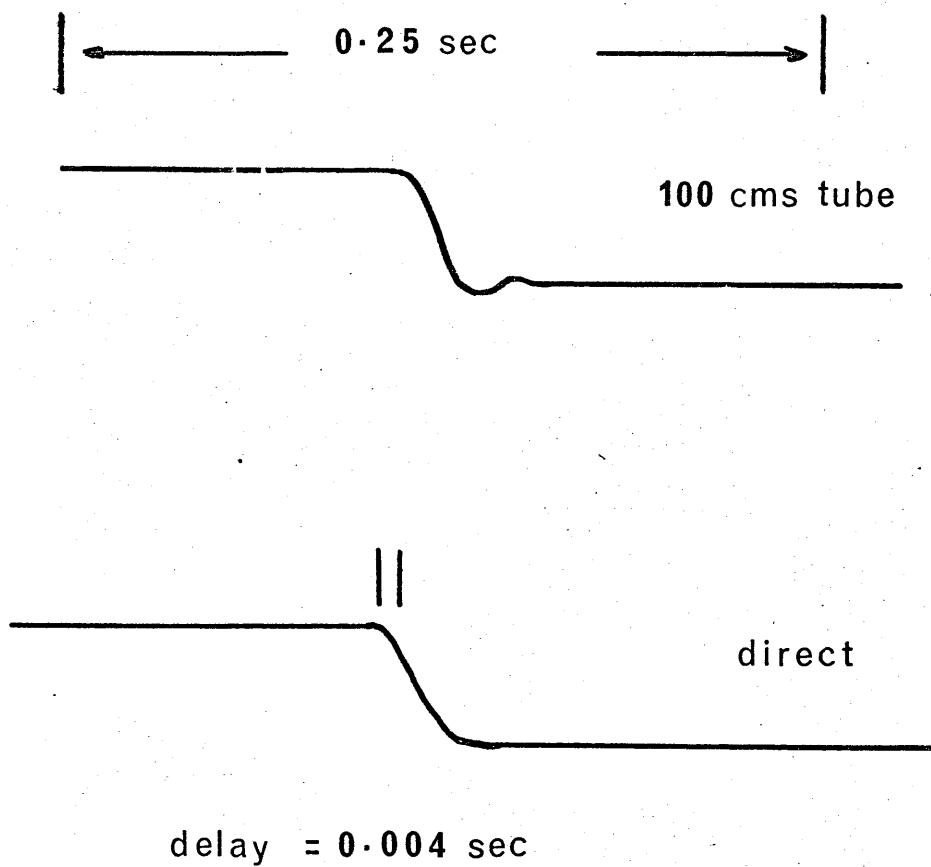
THE TEAT, FLOW IMPEDANCE AND MILK RESERVOIR.

FIG. 5.10



apparatus used to test response
time of pressure monitoring system

FIG. 5.11



tracing of simultaneously recorded
transducer outputs

FIG. 5.12

In practice the change in output voltage is much smaller, some infants only producing pressure changes of the order of 980 N/m^2 . Direct amplification of the corresponding voltage changes is impossible because of the high offset voltage. The circuit external to the transducer is shown in FIG.5.8, an adder being used to adjust the output from the transducer at atmospheric pressure to zero volts. The voltage changes are then amplified at switched gains of 10, 5 and 2.

The apparatus was calibrated against a glass U-tube manometer filled with I.M.S. (density 0.8 gm/cc) The results are shown in FIG.5.9 for the x2 amplifier.

FIG.5.10 shows the teat, the flow regulating impedance and the gastric feeding funnel used as a milk reservoir.

5.05 THE RESPONSE TIME OF THE PRESSURE MONITORING SYSTEM.

The effect of the catheter and length of silicone rubber tubing, connecting the mouth and the pressure transducer, on the response time of the system is an important factor, as it is the incidence of the pressure wave that is important.

The pressure transducer, silicone tube and catheter were connected to a small cylinder which had a second, identical transducer connected directly to it. (FIG.5.11) The pressure in the cylinder could be rapidly varied below atmospheric by opening a solenoid valve between the cylinder and a large reservoir tank, the pressure in the reservoir having previously reduced to 82 kN/m^2 . The volume of the reservoir was chosen so that the pressure did not significantly vary on opening the valve. The output voltages from the two transducers were simultaneously recorded with the result shown in FIG.5.12, which establishes

a response time of 0.004 seconds which is acceptable for the measurements to be made.

5.06 THE MICROPHONE.

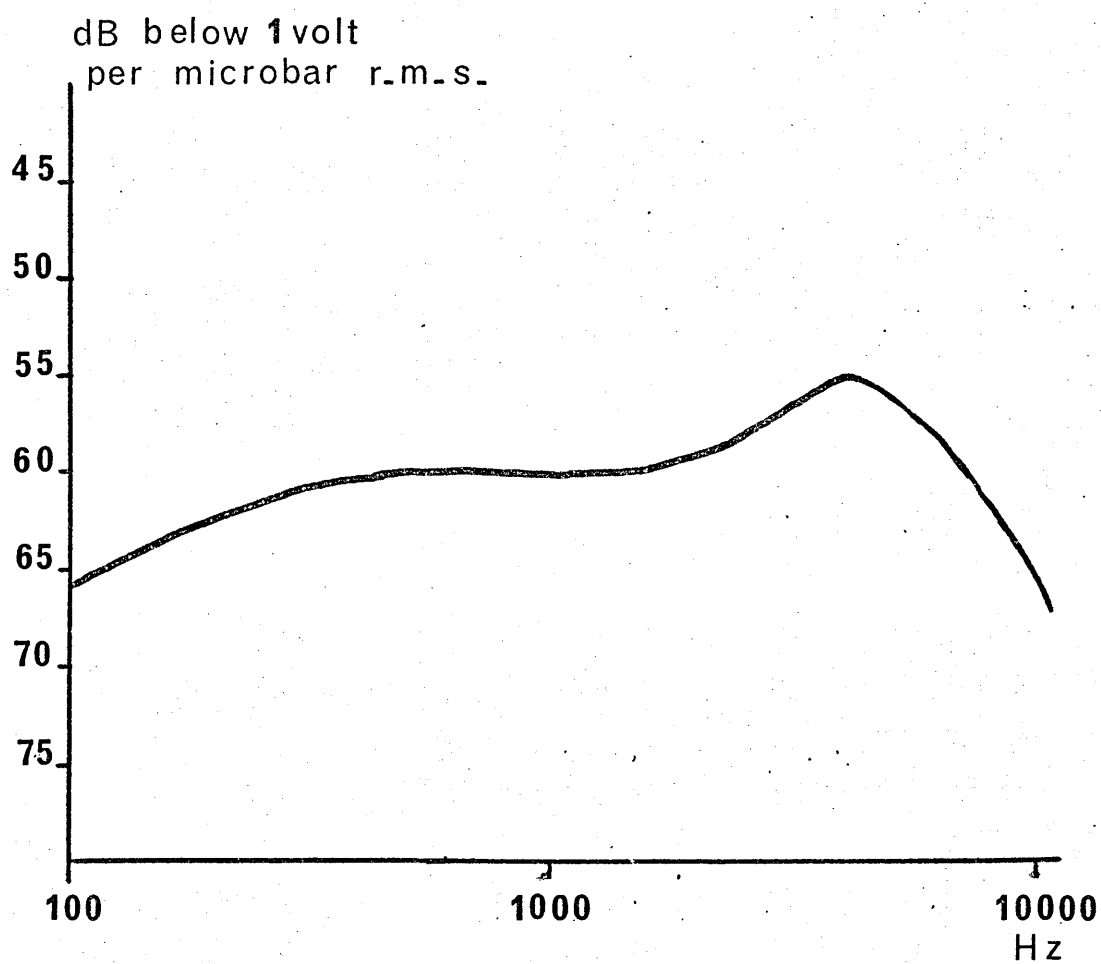
It is necessary for the microphone to be dimensionally small due to the size of the area of application, especially as it was hoped to monitor premature infants.

Logan et al (1967) described experiments involving frequency analysis of swallowing sounds recorded using a throat microphone and comparison of these sounds with those of respiration and vocalisation. These experiments showed that the sounds produced during deglutition consisted of intermittent bursts of sound energy with an irregular frequency distribution over the range 100 Hz to 8 kHz, and that these bursts of sound energy were randomly distributed in time. Nevertheless it was possible to distinguish clearly between deglutition, respiration and vocalisation patterns on a frequency spectrogram.

It is, therefore, also necessary for the microphone to have a reasonably flat frequency response over the range 100Hz to 8 kHz.

The sound transducer used was a Knowles Electronics, subminiature hearing-aid microphone. This was built into a specially designed housing to improve the acoustic coupling and to minimise artifact from skin and cable transmission.

The principle of operation of the transducer is that of a capacitance microphone using an electret film. To a first order of accuracy the microphone can be considered as a cylindrical parallel plate capacitor, one plate being the conducting foil diaphragm, the insulated back plate comprising



frequency response of the Knowles
subminiature transducer

FIG. 5.13

the throat microphone

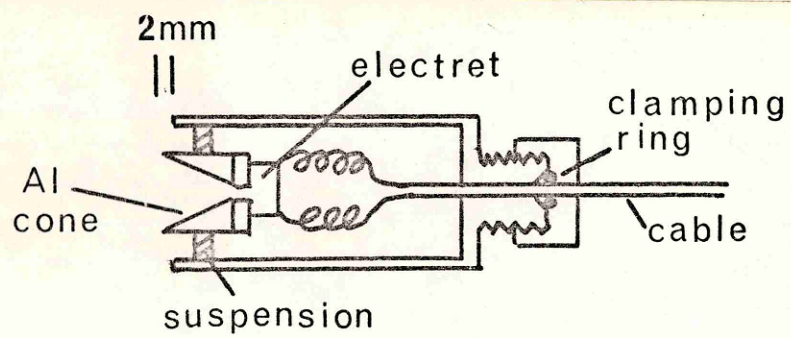
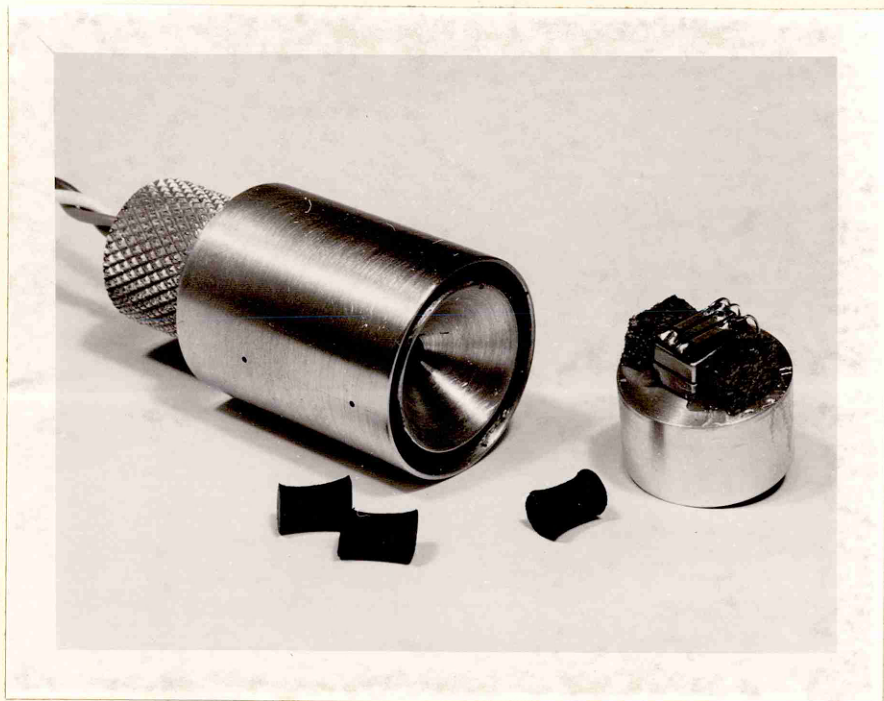


FIG. 5.14(a)

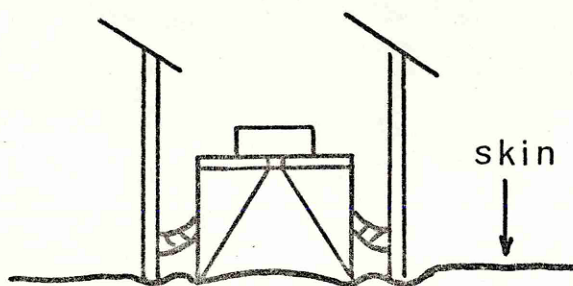
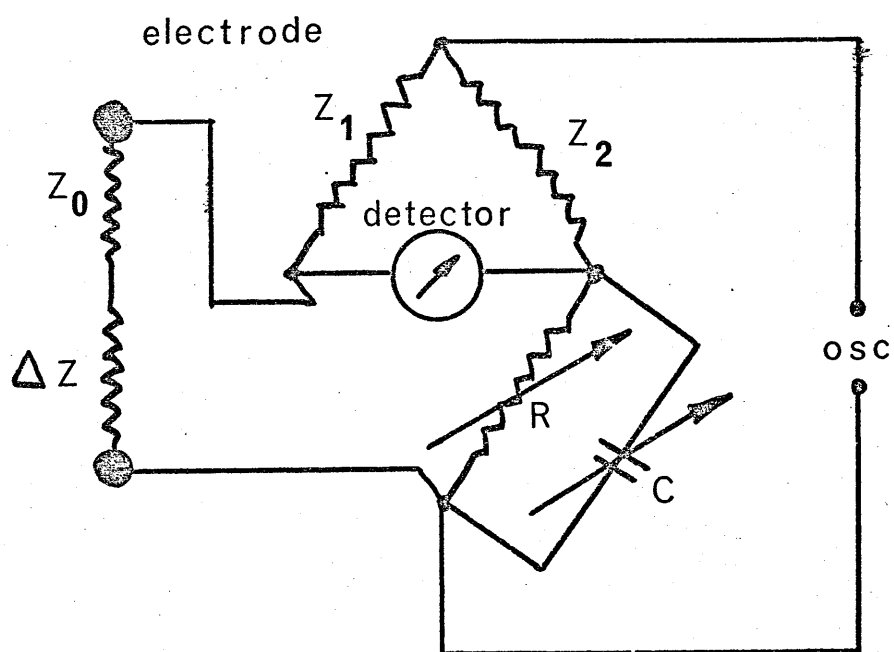


FIG. 5.14(b)



two electrode impedance
measuring circuit

FIG. 5.15

the other plate. The dielectric between the plates is partly air and partly plastic diaphragm material, in the case where the diaphragm is a metallised polyester film. The electret diaphragm flexes under the pressure of the incident sound wave, changing the capacitance of the cell.

The steady supply voltage required, for this particular device, is 1.5 volts and an integral F.E.T. amplifier provides an output of 0.2 to 0.9 volts with the frequency response shown in FIG.5.13.

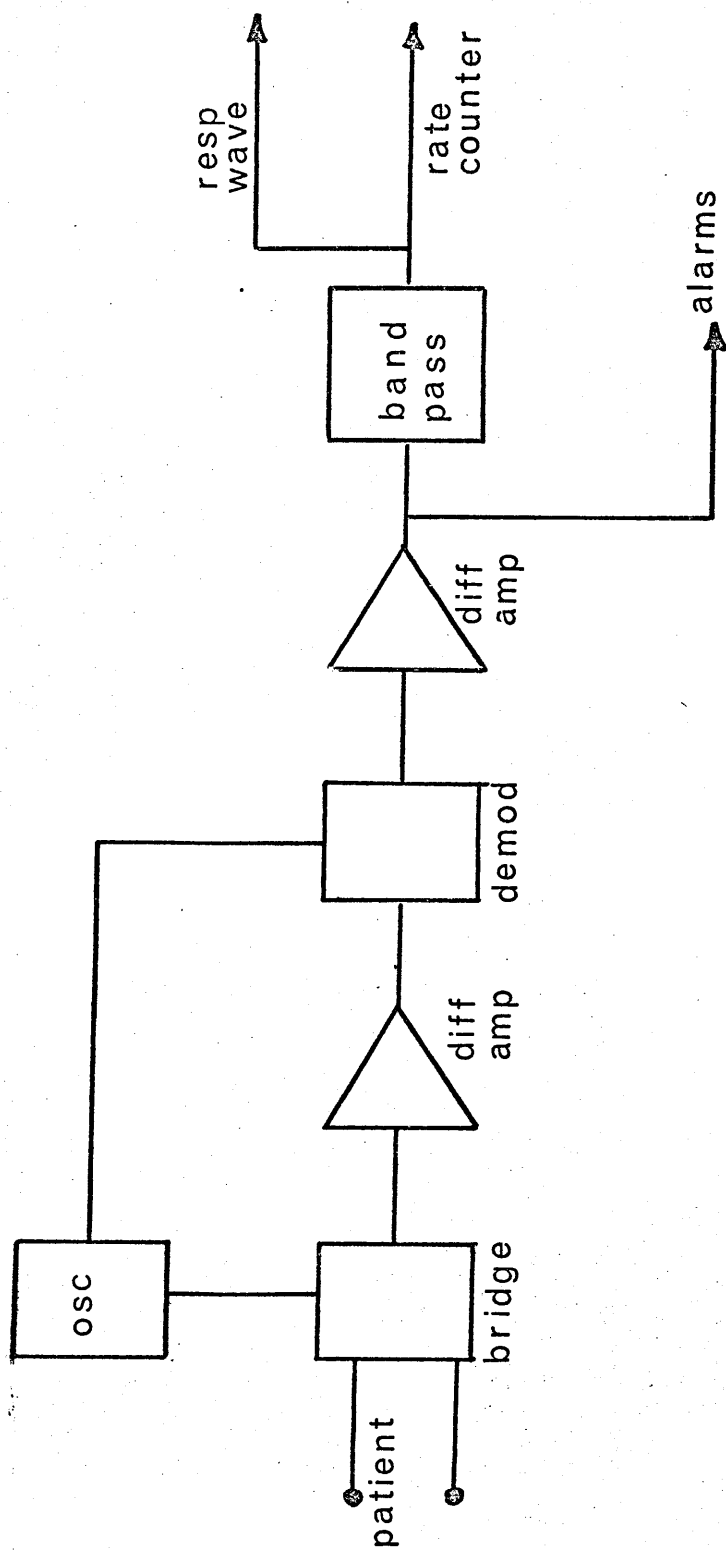
FIG.5.14(a) shows the construction of the microphone housing. The transducer had its port at the apex of an aluminium cone, supported from the outer housing by small rubizote studs. The connecting lead was clamped by an 'O' ring to attenuate sound transmission along the lead. The final connection to the microphone was made using fine (36 s.w.g.) coiled copper wires.

FIG.5.14(b) shows that when the microphone assembly was held gently against the skin a set was produced in the skin between the inner cone and the outer housing thus effectively attenuating sound transmitted along the skin. The air column trapped in the cone provides effective acoustic coupling to the transducer diaphragm.

5.07 IMPEDANCE PNEUMOGRAPHY AND THE HEWLETT PACKARD

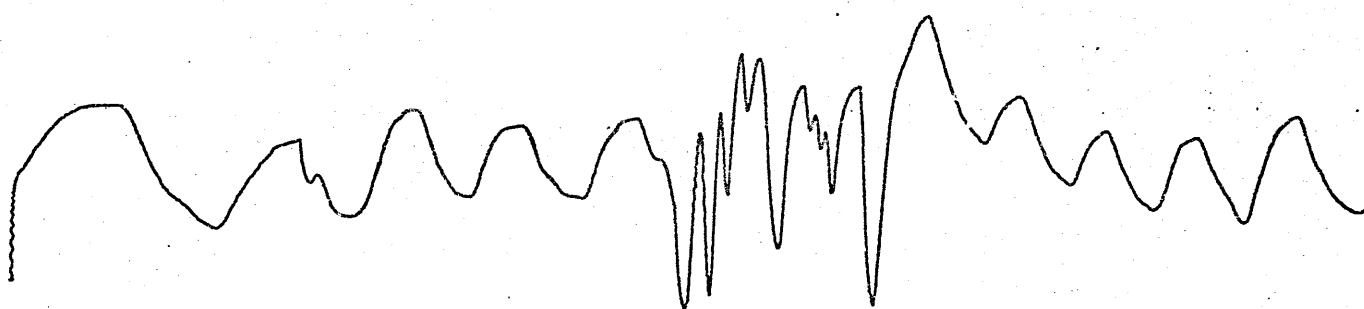
APNOEAMONITOR.

Two electrodes are attached to either side of the thorax; dimensional changes of the thorax give rise to changes in the impedance between the electrodes and this is used as an indication of respiration. The circuit in FIG.5.15 is the basic one for two-electrode impedance measurement. In such an arrangement the oscillator voltage, E , is applied to opposite corners of the bridge and the detector to the other two corners. The



Hewlett Packard apnoe monitor

FIG. 5.16



respiration trace showing
electrode movement artifact.

FIG. 5.17

ratio arms Z_1 and Z_2 are resistors of equal value thus the impedance bridge is a comparison bridge. The bridge is balanced for a base impedance, Z_0 , between the electrode terminals and changes in Z_0 , ΔZ , unbalance the bridge and register a voltage change on the detector. Precautions must be taken to avoid the magnitude of the output voltage becoming dependent on the value of Z_0 . For the same ΔZ , if Z_0 is small, more current will flow through Z_1 and Z_0 producing an output, ΔE_0 , which will be large. This sensitivity dependence on Z_0 can be eliminated by making Z_1 much greater than $Z_0 + \Delta Z$, which allows the bridge to have characteristics approaching those of a constant current circuit.

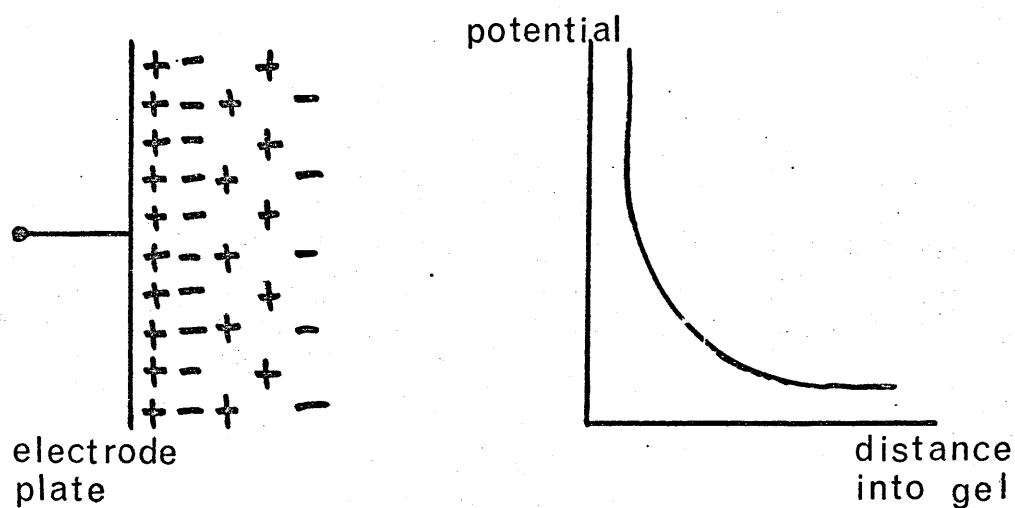
The Hewlett Packard Apnoeamonitor is basically a two-electrode impedance monitor with internal processing to provide outputs of respiration rate and apnoea alarm, but it also has a respiration wave output socket on its rear panel.

Power is supplied to the impedance bridge by a 65 kHz oscillator and the amplitude variations of the bridge output are demodulated and filtered to remove any 65 kHz. The signal then passes to a switch and on to trigger and averaging circuits to produce a reading of respiration rate. (FIG. 5.16) The respiration wave output is taken from a point immediately after the band pass amplifier.

The following sections are a discussion of the problems encountered in using this type of equipment.

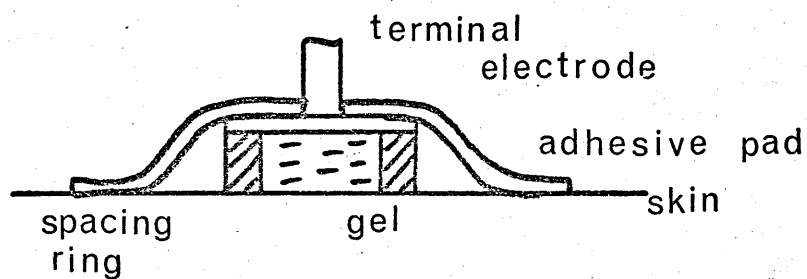
a) ELECTRODE PROBLEMS.

One of the first problems encountered was movement artifact from the electrodes. FIG. 5.17 is a tracing showing the effect of this movement artifact on the respiration wave.



potential distribution at the
electrode - electrolyte interface

FIG. 5.18



distance stabilised electrode

FIG. 5.19

Electrodes for measuring bio-electric events are attached to the skin with a layer of electrode gel, normally containing sodium chloride, between the electrode plate and the skin. Examination of the electrode-electrolyte junction at an ionic level helps to explain the movement artifact.

Geddes (1972) discusses in detail the various possibilities of charge distribution at an electrode-electrolyte interface. These depend on the type of metal used as the electrode material and the composition of the electrolyte. It is this ionic distribution, arising from the reaction of the electrode with electrolyte, that endows an electrode with its properties. FIG.5.18 shows a typical ionic distribution and the resulting potential.

Any movement of the electrode produces momentary changes in the ionic distribution and hence changes in potential. The latter can be quite large giving the unwanted artifact.

This problem may be satisfactorily overcome by stabilising the electrode plate to skin spacing (FIG. 5.19). This involved the manufacture of small plastic ring spacers which were filled with electrode gel and placed between the electrode plate and the skin. Once fixed in position with an adhesive pad the electrode-skin distance remained constant. A similar type of stabilised electrode is now commercially available but is far too large for use on neonates.

b) TIME COINCIDENCE PROBLEMS.

On studying charts from recordings of feeding neonates, who were judged normal by medical staff, it was noticed that the trace indicating respiration was, on occasions, coincident

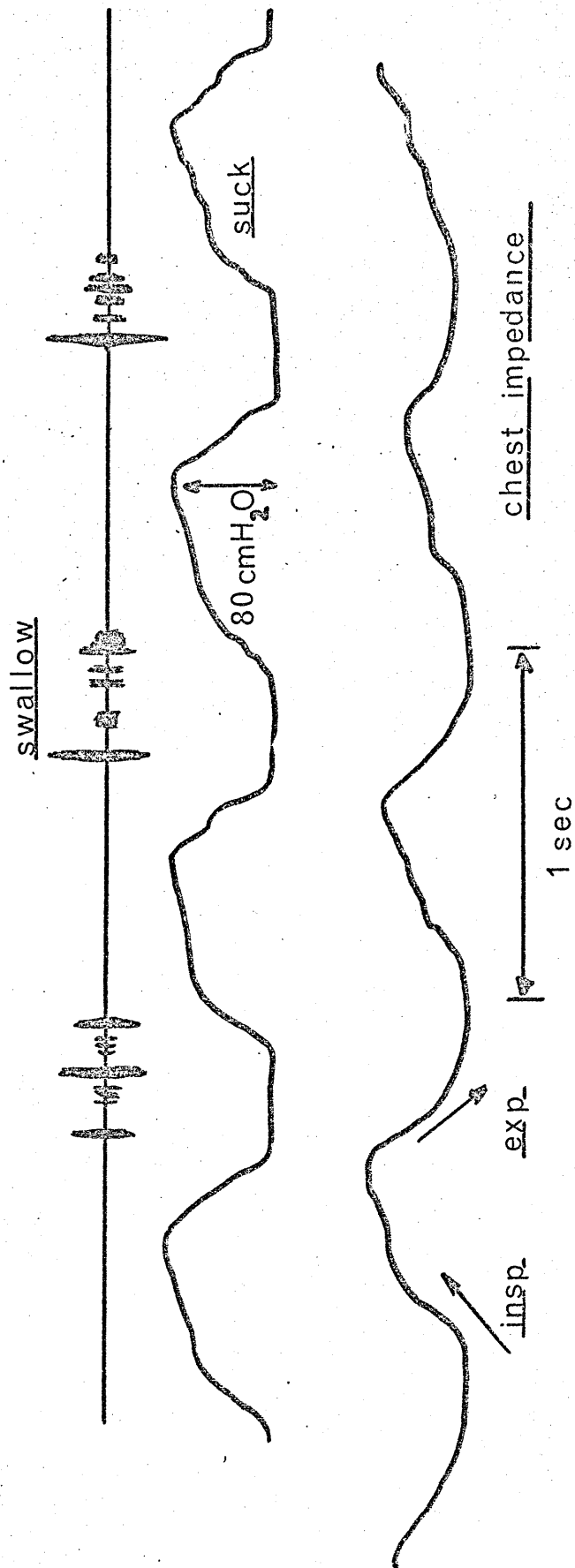


FIG. 5.20

tracing showing impedance artifact.

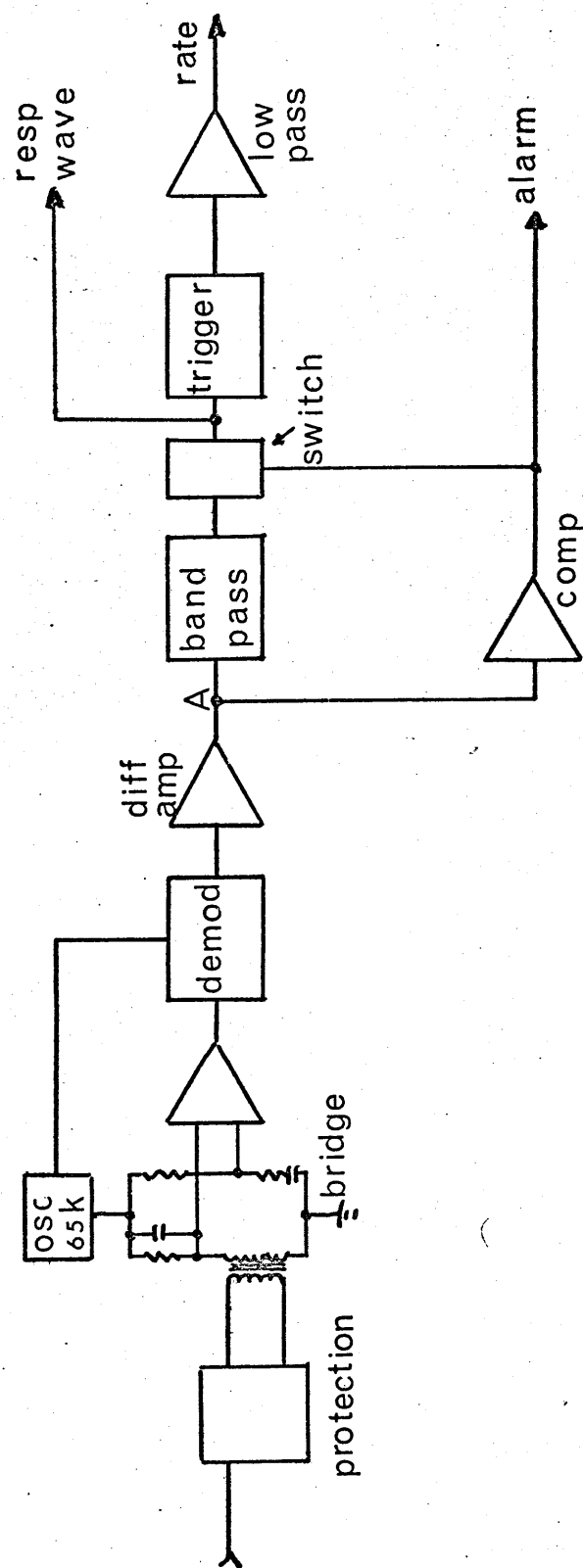
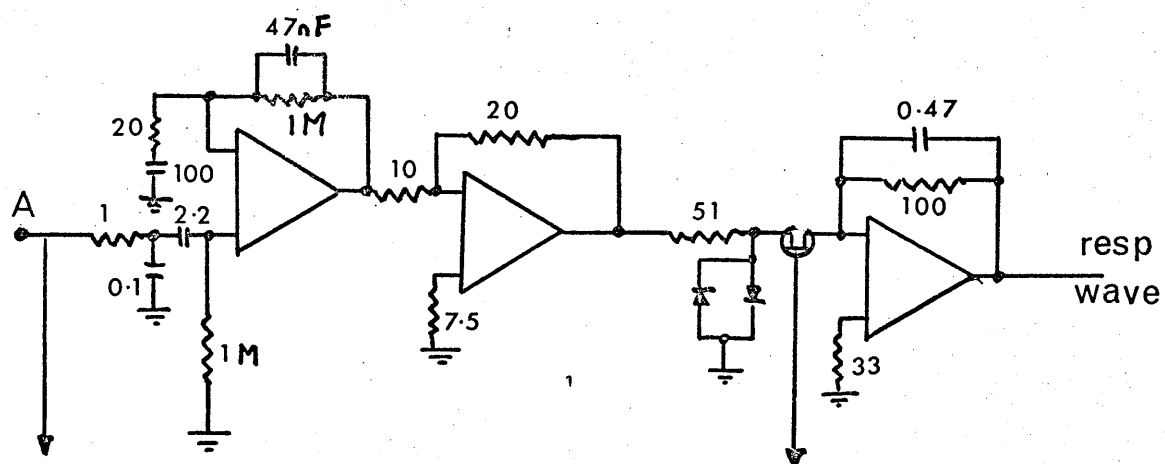


FIG. 5.21

schematic of the Hewlett Packard apnoea monitor



(resistance values in kilohm)

detail of the band pass amplifier

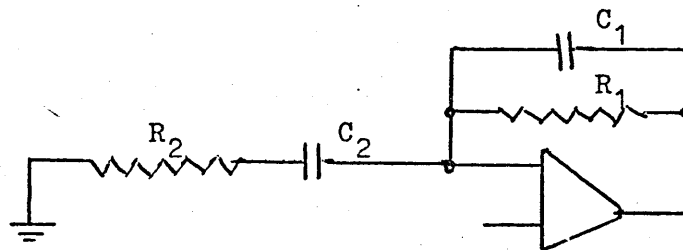
FIG. 5.22

with swallowing.(FIG. 5.20) This is a physiological impossibility without choking. Suspicion therefore fell on the Hewlett Packard apnoeamonitor and a closer study of its output properties was carried out.

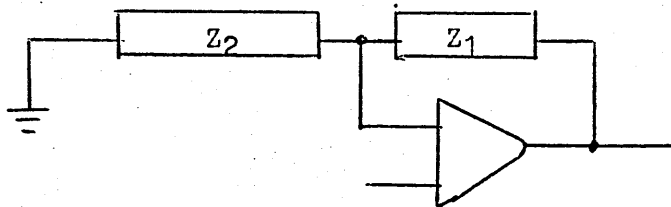
It was hoped that an explanation would be found when a circuit diagram for the H.P. apnoeamonitor, schematically shown in FIG.5.21, was examined and the band pass amplifier, detailed in FIG.5.22, analysed to see if its phase shift could cause the artifact.

The input circuit to the band pass amplifier contains a low pass filter to remove any 65kHz present after demodulation.

The feedback circuit, responsible for the gain of the amplifier, may be analysed using the circuit parameters given in the following diagram,



which may be represented in a further diagram as follows:-



The gain, G , is given by:-

$$G = 1 + \frac{Z_1}{Z_2}$$

$$Z_1 = \frac{R_1}{1 + j\omega C_1 R_1}$$

$$Z_2 = R_2 + \frac{1}{j\omega C_2}$$

$$G = 1 + \left(\frac{R_1}{1 + \frac{j\omega C_1 R_1}{j\omega C_1 R_1}} \right) \left(\frac{j\omega C_2}{1 + j\omega C_2 R_2} \right)$$

which can be rationalised to give :-

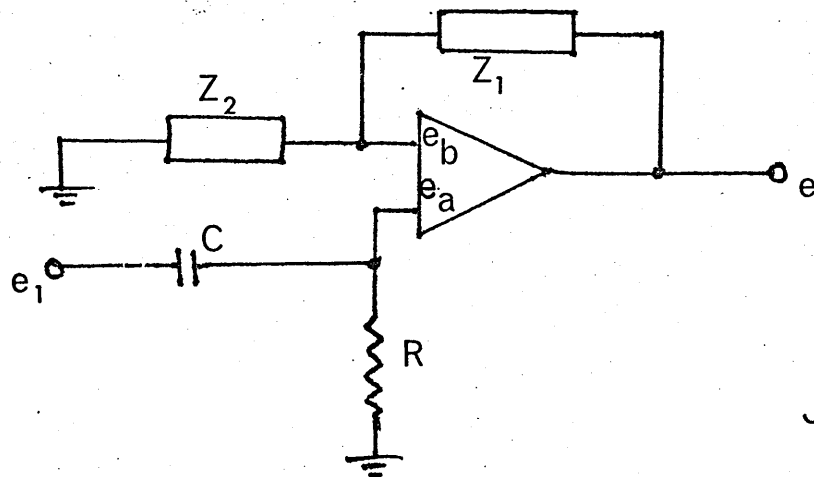
$$G = 1 + \left(\frac{j\omega R_1 C_2 + \omega^2 C_2^2 R_1 R_2 + \omega^2 C_1 C_2 R_1^2 - j\omega^3 C_1 C_2^2 R_1^2 R_2}{1 + \omega^2 C_2^2 R_2^2 + \omega^2 C_1^2 R_1^2 + \omega^4 C_1^2 R_1^2 C_2^2 R_2^2} \right)$$

Equating real and imaginary parts :-

$$X' = \frac{100\omega - 9.4\omega^3}{1 + 4\omega^2 + 8.8 \times 10^{-3}\omega^4} \quad \text{--- 5}$$

$$R' = 1 + \left(\frac{205\omega^2}{1 + 4\omega^2 + 8.8 \times 10^{-3}\omega^4} \right) \quad \text{--- 6}$$

This equivalent feed-back circuit can then be used to examine the whole circuit shown in the following diagram.



From the previous page :-

$$e_a = \frac{R}{R_1 + 1/j\omega C} \cdot e_1$$

$$e_b = \frac{Z_2}{Z_1 + Z_2} \cdot e$$

But :- $e_a = e_b$

$$\therefore \frac{e_1 R}{R + 1/j\omega C} = \frac{e Z_2}{Z_1 + Z_2}$$

From values given on previous page:-

~~From 586~~ :- $\frac{e}{e_1} = (R' + jX') \left(\frac{j\omega CR}{1 + j\omega CR} \right)$

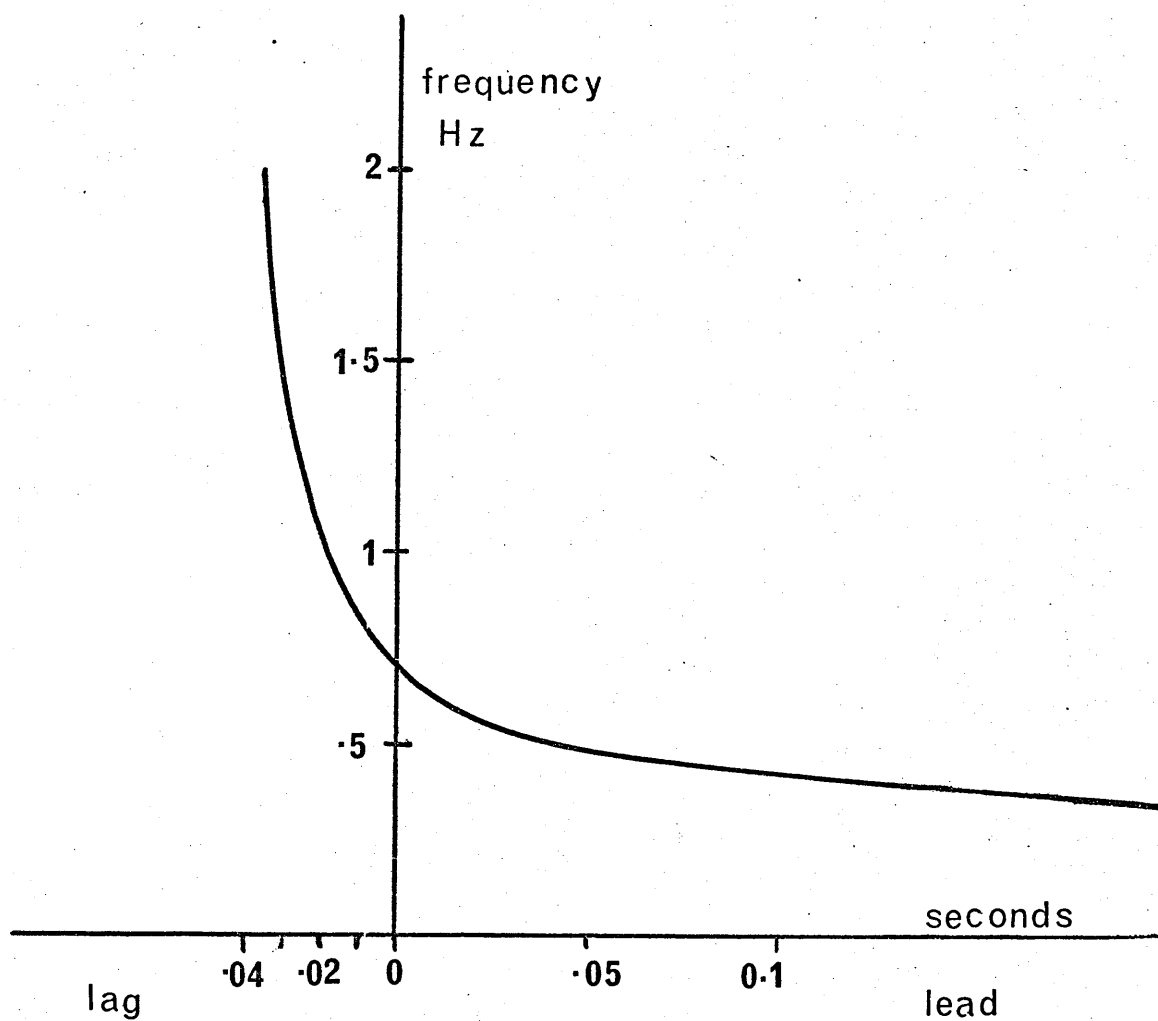
which can be rationalised to give :-

$$\frac{e}{e_1} = \frac{(R' + jX') (j\omega CR + \omega^2 C^2 R^2)}{(1 + \omega^2 C^2 R^2)}$$

Equating real and imaginary parts :-

$$\frac{X'_2}{R'_2} = \frac{\omega C R R' + \omega^2 C^2 R^2 X'}{\omega^2 C^2 R^2 R' - \omega C R X'}$$

$$= \tan \phi \quad (\text{where } \phi = \text{the phase angle.})$$



variation of phase shift with
respiration frequency

FIG. 5.23

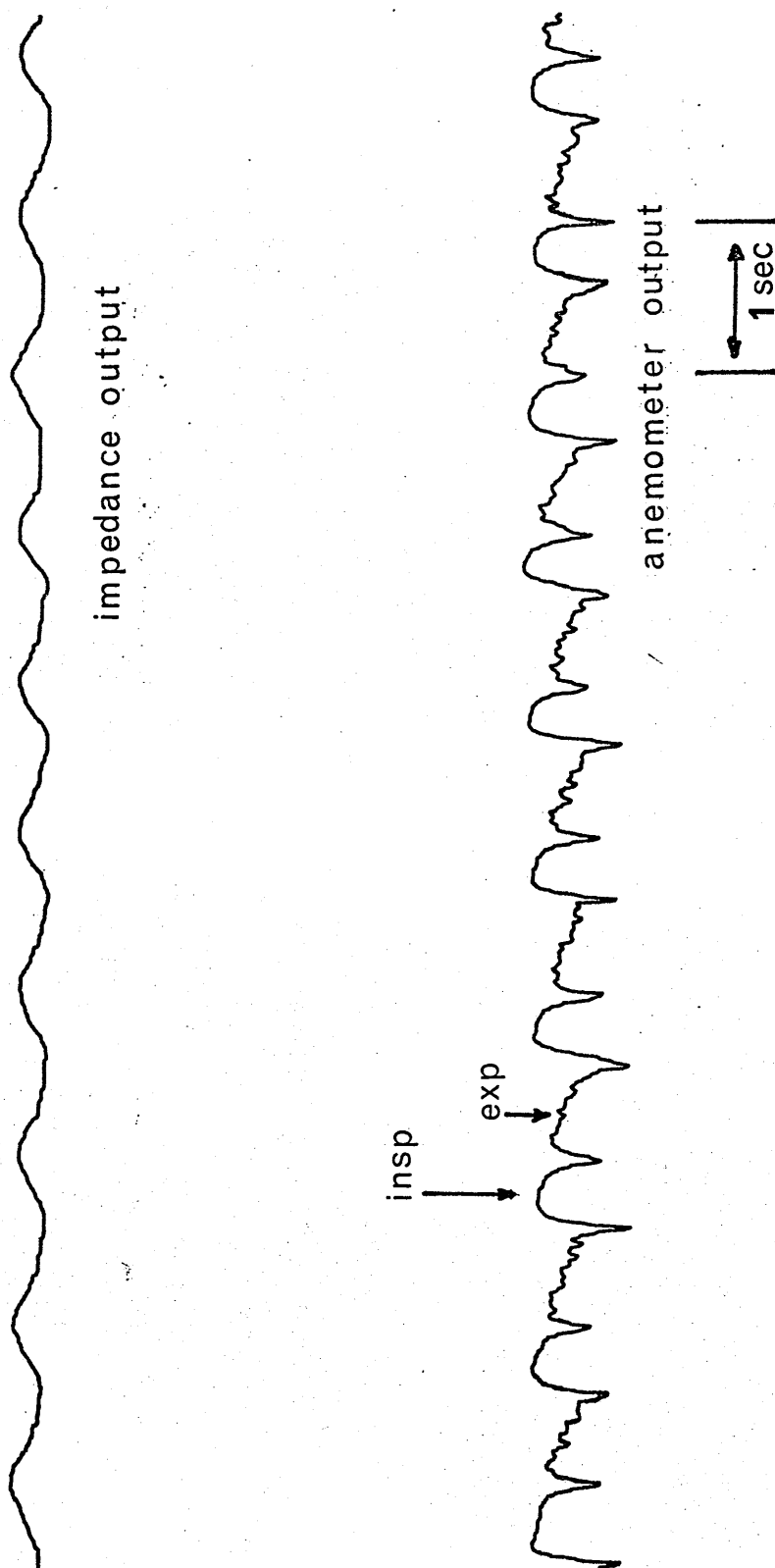


FIG. 5.24

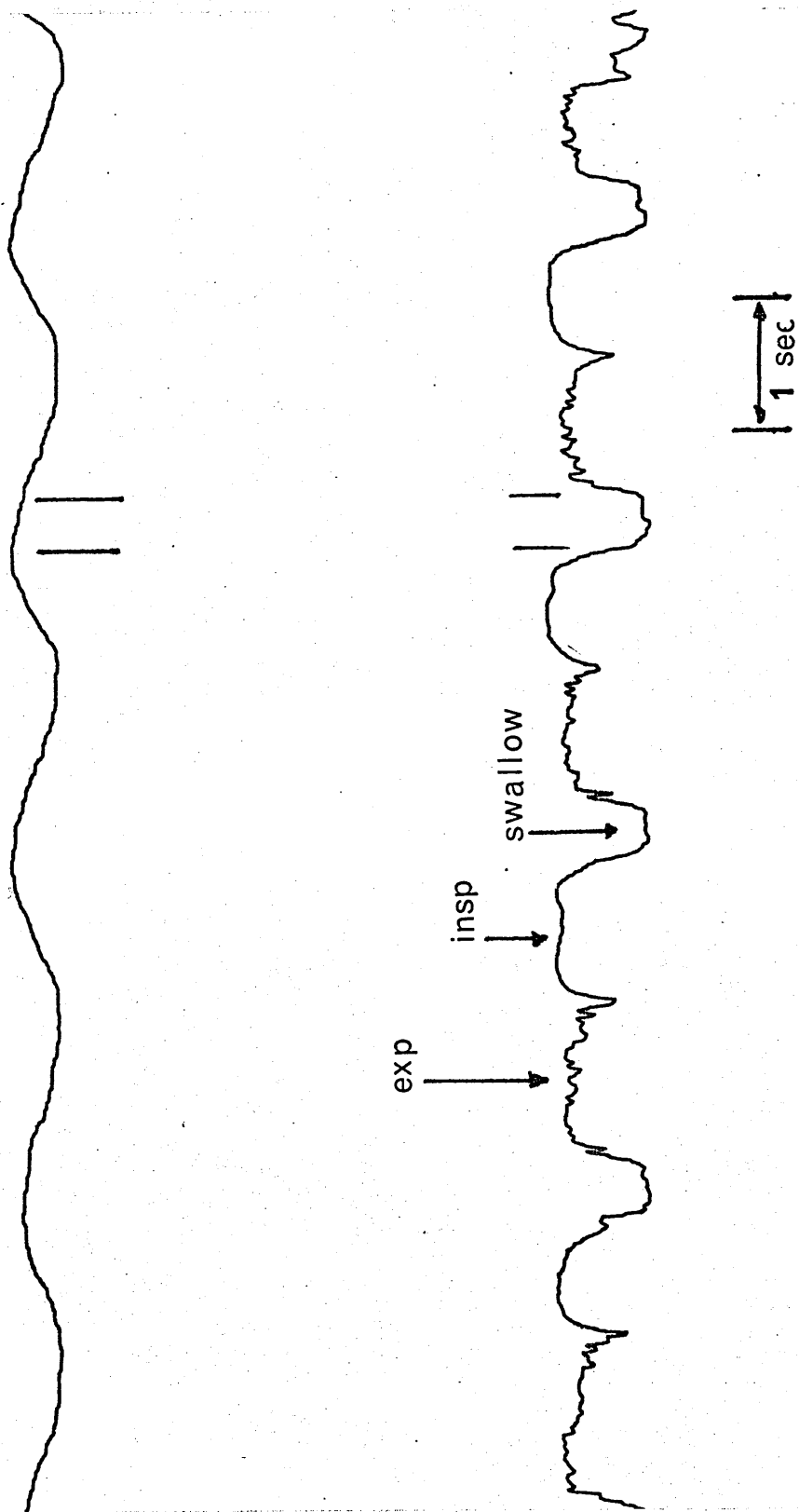


FIG. 5.25

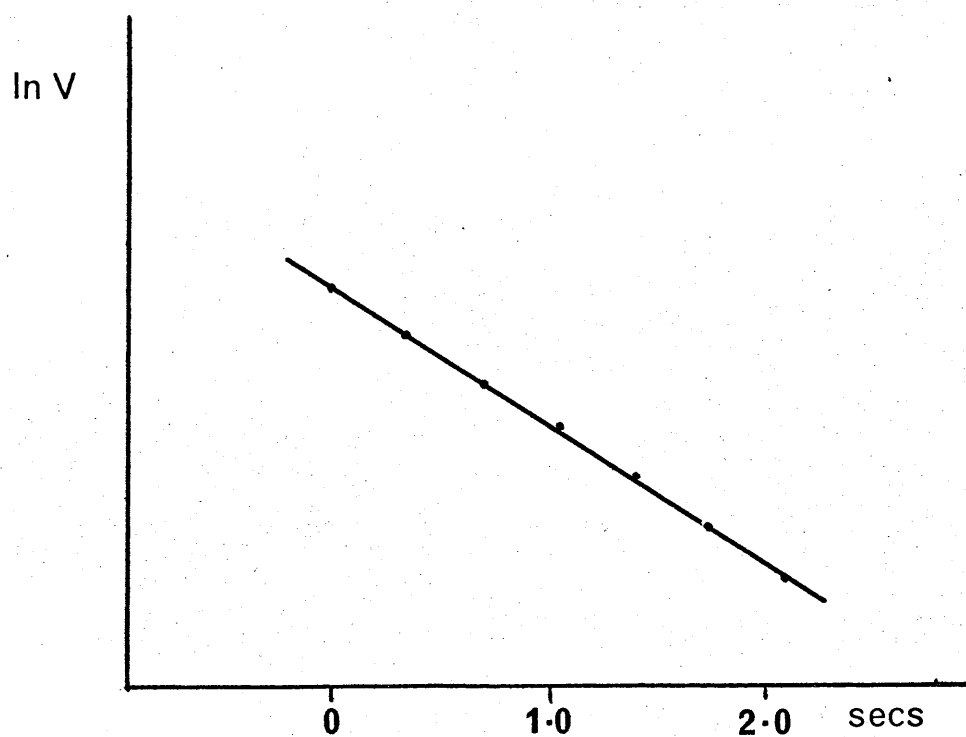
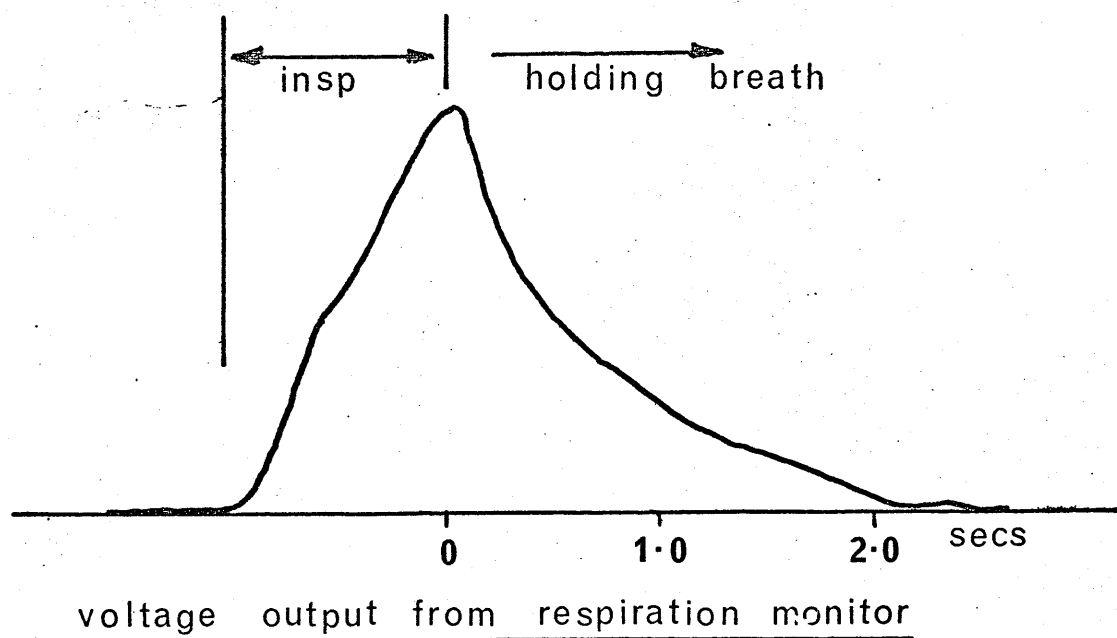


FIG. 5.26

A plot of this phase shift in seconds against frequency of signal is shown in FIG.5.23. It is clear that the phase shift at the frequencies concerned is not significant and does not explain the trace discrepancy.

The H.P. apnoeamonitor was brought into the laboratory and the next series of tests carried out on the author.

Chest electrodes were fitted and the respiration wave output recorded simultaneously with the output from the nasal anemometer. The nasal anemometer mask was held over the nose and steady respiration made through the nose only. The results are shown in FIG.5.24 for respiration only and FIG.5.25 for respiration with intervals for swallowing. The anemometer output clearly demonstrates an arrest in respiration during swallow sequences but the impedance device still registered a change; the flattened wave peaks appear to be $1/8^{\text{th}}$ ^{cycle} ~~the~~ out of phase with the respiration arrests.

Using the apnoeamonitor alone a slow inspiration was performed and the breath then held for several seconds. The resultant output trace is shown in FIG.5.26. An exponential decay of the output voltage occurs from the point of inspiratory arrest. Plotting $\ln V$ against time for this curve gives a straight line which can be used to calculate the time constant, CR, of the circuit responsible.

Where:-

$$V = V_0 e^{-t/CR} .$$

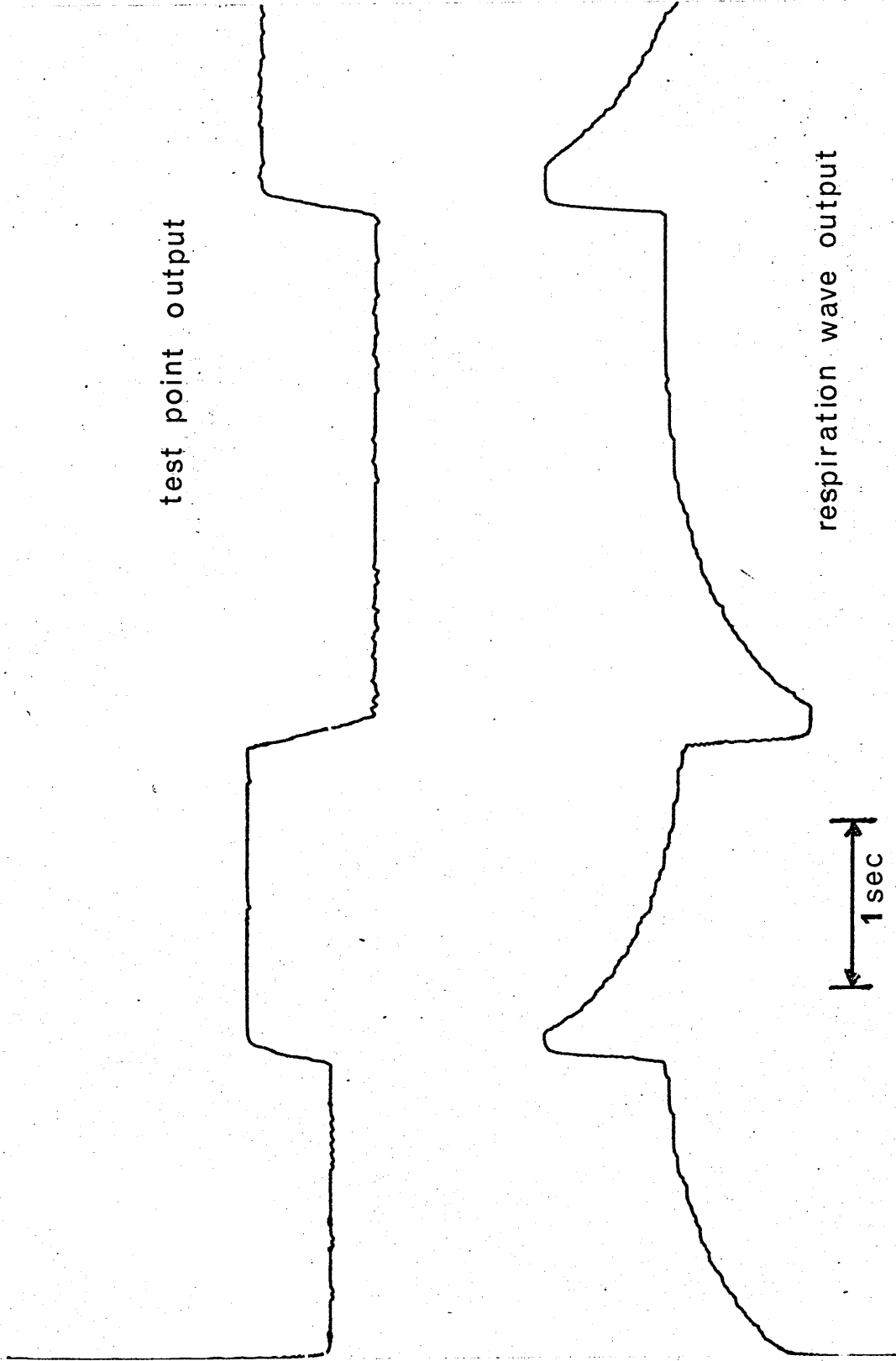


FIG. 5.27

$$\ln V = \ln V_0 - t/CR$$

From the graph :-

$$-1/CR = -1.4$$

$$\underline{\text{Time constant } CR = 0.714 \text{ sec}^{-1}}$$

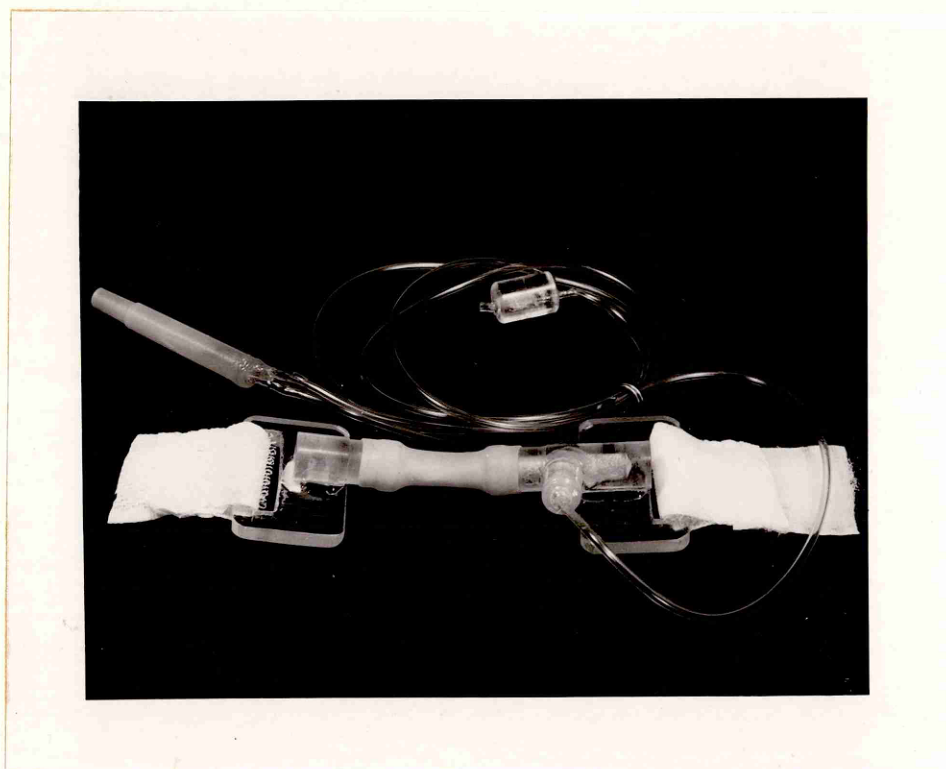
To verify that this effect was produced in the band pass amplifier circuits the electrode connections were switched between 800 Ω and 1 k Ω fixed resistors and the respiration wave output and a test output from point A, FIG.5.21, monitored simultaneously. The result is shown in FIG.5.27.

The time constant of the R.C. circuit connected to the non-inverting input of the band pass amplifier integrated circuit is :-

$$2.2 \times 10^{-6} \times 1 \times 10^6 = 2.2 \text{ secs.}$$

but this assumes that the input impedance of the integrated circuit is infinite. The quoted range of input resistance for a typical operational amplifier, SN72741, is 1 M Ω typical, min. value 0.3 M Ω so that one might expect the time constant to vary from 0.55 secs. to 1.1 secs. thus bracketing the observed value.

The explanation therefore appears to be that the 2.2 μ F capacitor and the equivalent of 500 k Ω to ground form a differentiating circuit of long time constant but small phase angle, in contradiction to a fast differentiator which would produce approximately 90° phase shift.



THE BALLOON PNEUMOGRAPH.

FIG. 5.28

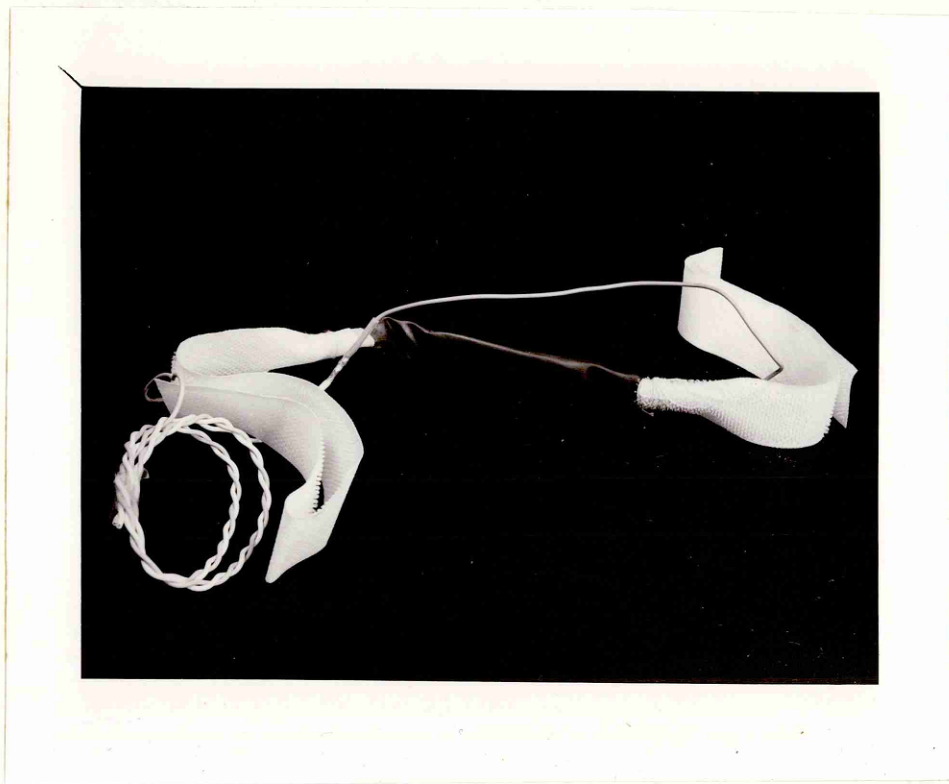
5.08 THE BALLOON PNEUMOGRAPH.

A length of slightly inflated, thin walled, flexible tube is fastened around the chest. The expansion and contraction of the chest and hence the change in length of the long thin balloon produces pressure variations of the filling medium. These pressure changes can be used to monitor respiration.

This type of device had to be modified for use on neonates because the infant is always supported at its back. Any movement would cause the balloon to be compressed by varying amounts and hence produce artifact.

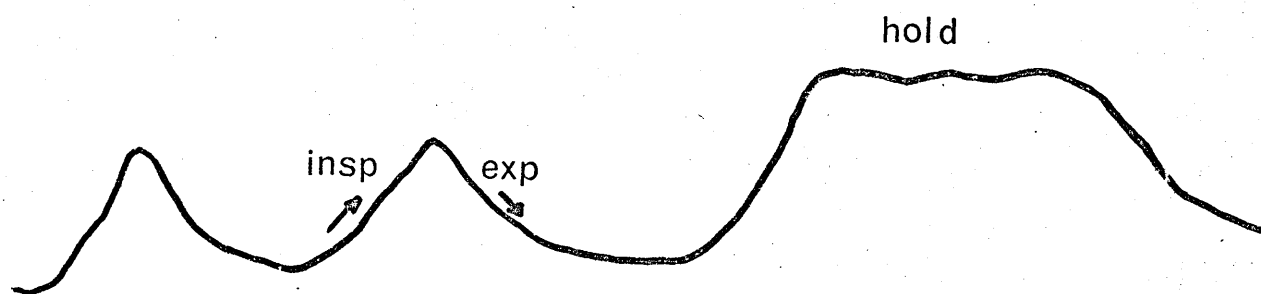
The apparatus constructed for this work consisted of a short length of latex tubing, 5mm diameter, connected by a 1mm catheter to a pressure transducer of the type described in an earlier section (LX1602A). Connection to an elasticated fastening was made at each end of the tube by plastic end-pieces shown in FIG.5.28, one of which carried the catheter connection. The volumes of all connecting tubes etc. were kept as small as possible, compared to the balloon volume, as these constituted a dead space. The device could be fastened around the infant's thorax with the balloon at the front. Small changes in chest dimensions produced adequate variations in pressure for the device to be useful although an offset correction was necessary after each fitting to compensate for variations in tension of the elasticated fastening.

The main objection to the use of this device eventually came from clinicians, who felt that the definite force required to extend the inflated balloon could place too much constriction on the infant's breathing if wrongly applied. The technique was therefore abandoned.

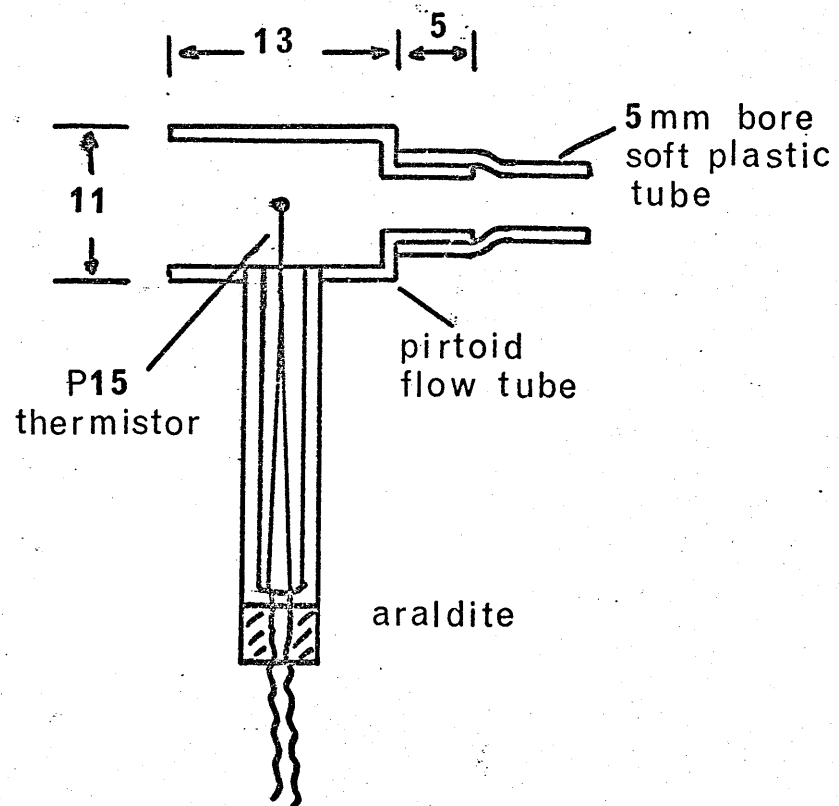


THE CONDUCTIVE FOAM PNEUMOGRAPH.

FIG. 5.29



respiration wave from foam pneumograph



small anemometer head used
as a respiration monitor

FIG. 5.31

5.09 THE CONDUCTIVE FOAM PNEUMOGRAPH.

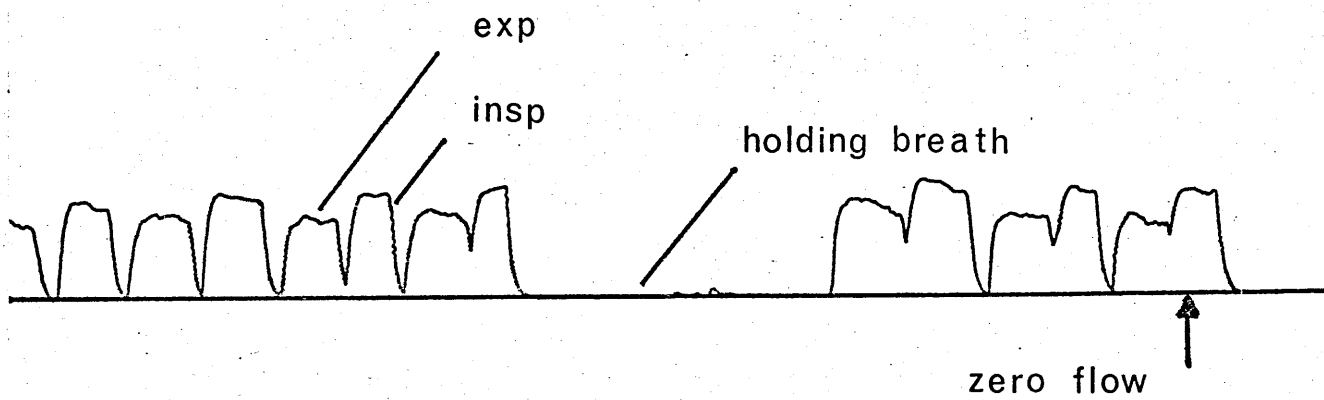
A second pneumograph was constructed using a strip of graphite loaded foam as a movement transducer. The foam was 70mm long, 15mm wide and 1.5mm thick with electrical connections made at each end by crimping copper 'spades' to the strip. The strip was made to fasten around the infant's thorax by means of a very light elastic belt. The change in resistance of the foam strip could then be used to monitor chest movements. The relaxed resistance of $20k\Omega$ rose to $50k\Omega$ with an extension of 10mm. FIG.5.29 shows the foam pneumograph and FIG.5.30 shows a typical respiration sequence, of an adult, using this technique.

This technique was abandoned because a latex covering was required to keep the foam from contact with the infant and to allow sterilisation; this again exerted a definite force on the infant thorax.

5.10 THE ANEMOMETER RESPIRATION MONITOR.

Fortunately the nasal anemometer system, previously described, was being developed at the same time as the respiration monitors. Infants of the ages being monitored are 'nose-breathers' and it was therefore obvious that a small anemometer head, placed beneath one nostril, would give a definite indication of airflow and also the instant of commencement and cessation.

The operation of the thermistor device is described in the first part of this work, but a voltage-controlled - oscillator was not required as the instrumentation recorder was capable of accepting D.C. signals of up to 10 volts. The anemometer head was constructed as shown in FIG.5.31 using the same type of thermistor (P15) as before.



inspiration, expiration effect on anemometer
output

FIG. 5.32

Under steady temperature conditions the heated thermistor flow meter is a non-directional device, but in our mode of operation the exhaled air is warmer than inhaled air and, for equal speeds, the former will therefore have a smaller cooling effect. FIG.5.32 demonstrates the differences in the anemometer output for inspired and expired air when held beneath the nose of an adult.

Artifact can be produced by this apparatus with rapid movement of the head. As an infant during feeding is in a ' quiet ' state very little movement of the head occurs and therefore little artifact should be produced.

CHAPTER SIXTHE USE OF THE APPARATUS, DATA PRESENTATION AND RESULTS.6.01 THE USE OF THE APPARATUS IN CLINICAL SITUATIONS.a) SETTING UP AND STERILISING.

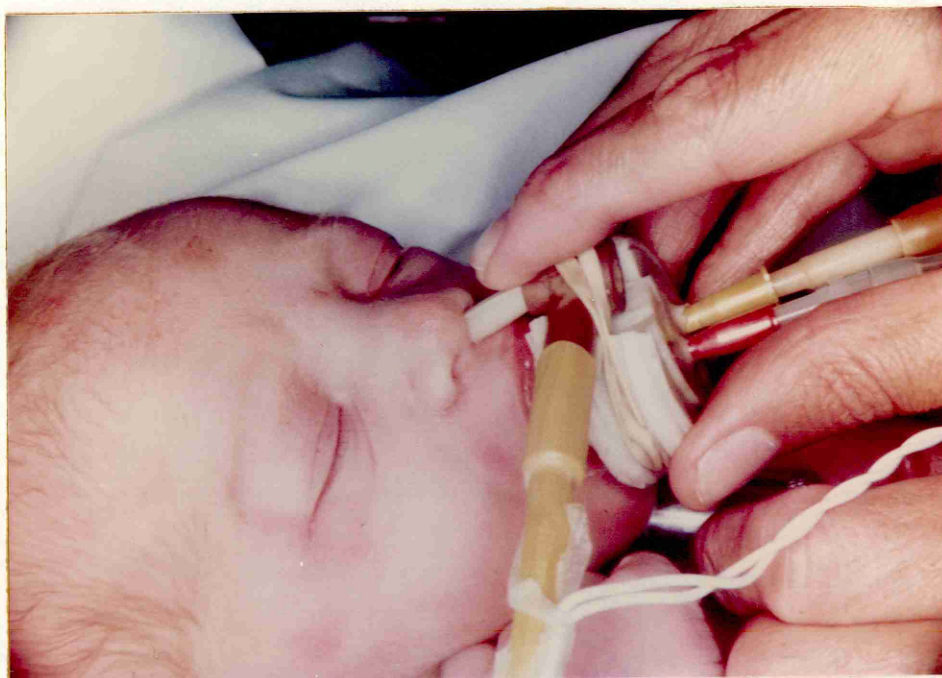
In order to standardise the feeding position, the infant was placed in a small plastic chair on a table. The rake of the chair was adjusted so that it held the patient in a semi-recumbent position. Waist straps held the infant firmly in position. The use of this chair allowed two operators to make the recordings without the aid of a nurse to hold the infant.

All the electronic apparatus was placed on a trolley at the side of the table. The milk reservoir was held in a clamp mounted on a drip stand. The position of this clamp could be varied so that the milk reservoir was level with the teat.

All tubes connecting the teat to the milk reservoir and pressure transducer, the flow impedance, the teat itself and all connecting pieces were sterilised by autoclave before use. The milk reservoir was disposable. The microphone and anemometer head were dip-sterilised with chlorohexidine in alcohol. A sterile, disposable plastic cover was spread over the chair before the infant was placed in position. All these precautions were necessary to prevent any spread of infection from infant to infant.

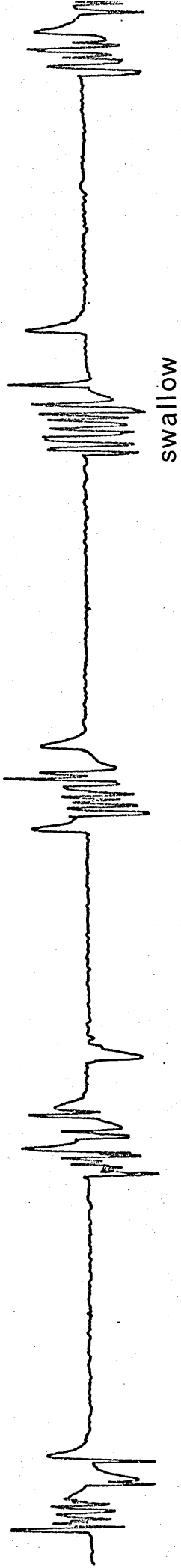
b) MAKING RECORDINGS.

The reservoir was filled with a measured quantity of milk, either breast or S.M.A. depending on the baby's normal diet. The milk was allowed to flow to the end of the teat and

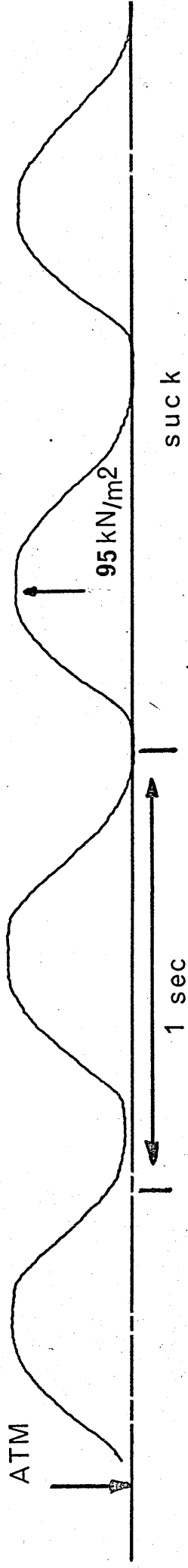


INFANT FEEDING ON THE STANDARDISED TEAT.

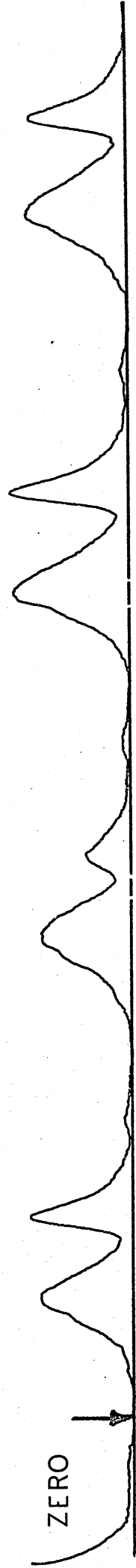
FIG. 6.1



swallow



suck



respiration

suck, swallow and respiration pattern (normal infant)

FIG. 6.2

the supply tube clamped. It was found necessary to have milk at the end of the teat to encourage the infant to suckle.

The teat was placed in the infant's mouth and the anemometer head positioned so that the soft plastic extension tube was in line with one nostril.(FIG. 6.1.) The milk supply tube was unclamped and the microphone placed in position over the carotid triangle.It was then necessary for a second operator to start the tape recorder and monitor the respiration and pressure indicators.

About two minutes of recording were made with each patient.

6.02 PRESENTING THE DATA.

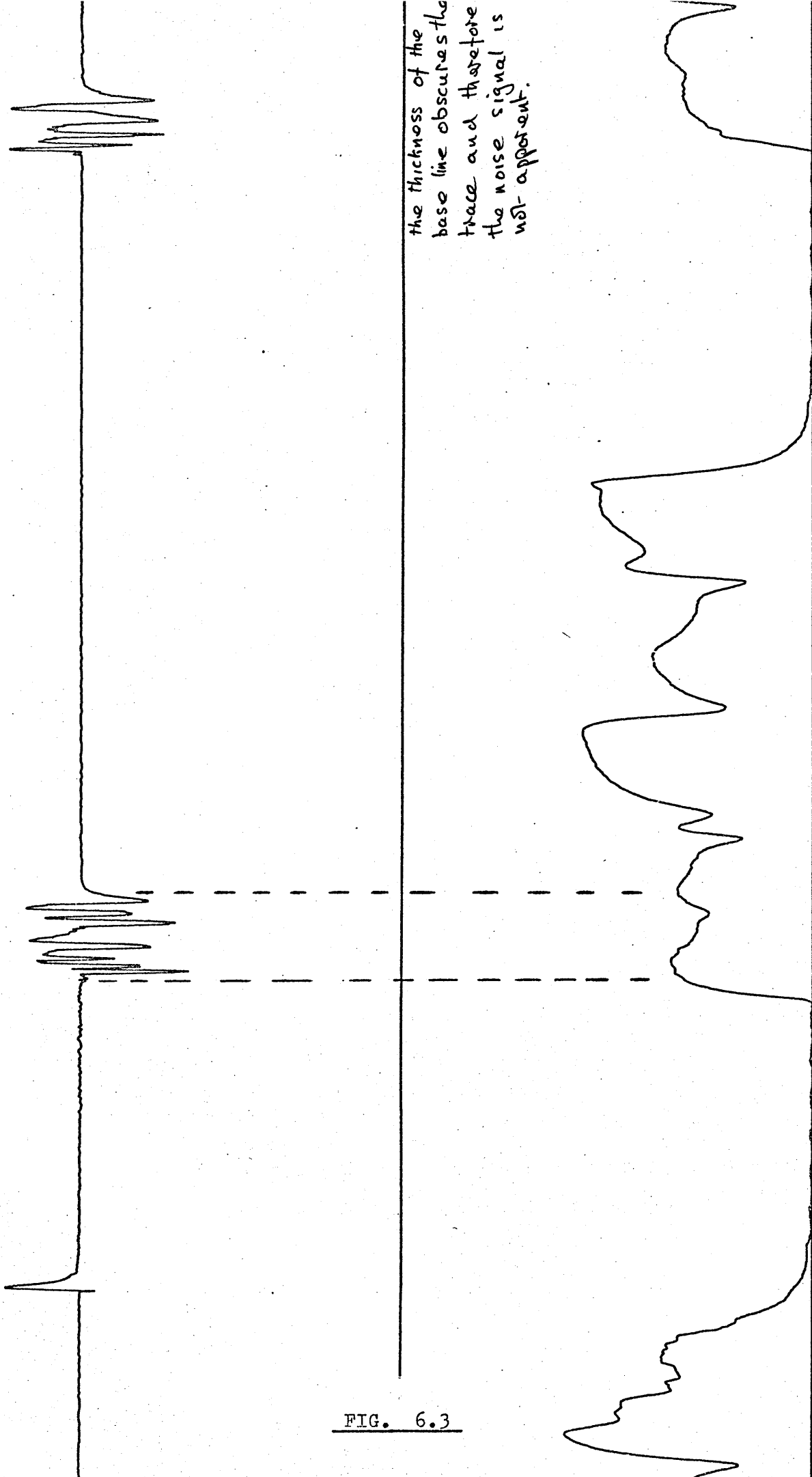
The tapes were returned to the laboratory for processing into chart form, which was done using either the ultraviolet lightwriter or the apparatus previously described for processing nasal anemometry charts. Processing using the latter takes a little longer as there are only two data channels available in the transient signal processor.

A typical chart of a normal neonate is shown in FIG. 6.2.

The respiration pattern is displayed as a uni-directional airflow because the thermistor anemometer only senses velocity changes not direction of flow, and although inspiration and expiration can be distinguished when a number of cycles are shown (FIG.5.32) it is difficult to be positive when only one cycle occurs.

6.03 DATA FROM NEONATES KNOWN TO BE ABNORMAL.

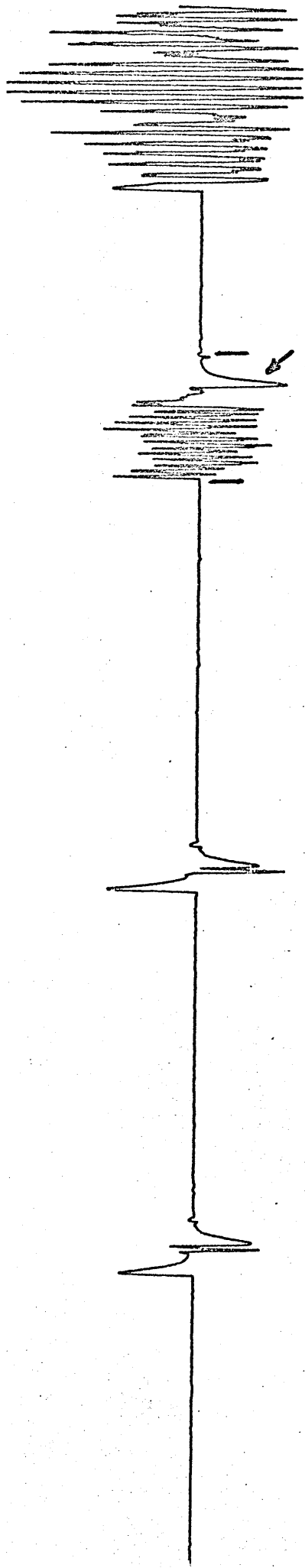
FIGS. 6.3 and 6.4 show traces of recordings made



the thickness of the
base line obscures the
trace and therefore
the noise signal is
not apparent.

FIG. 6.3

suck, swallow, respiration - submucous cleft



STRIDOR

98.5 kN/m²

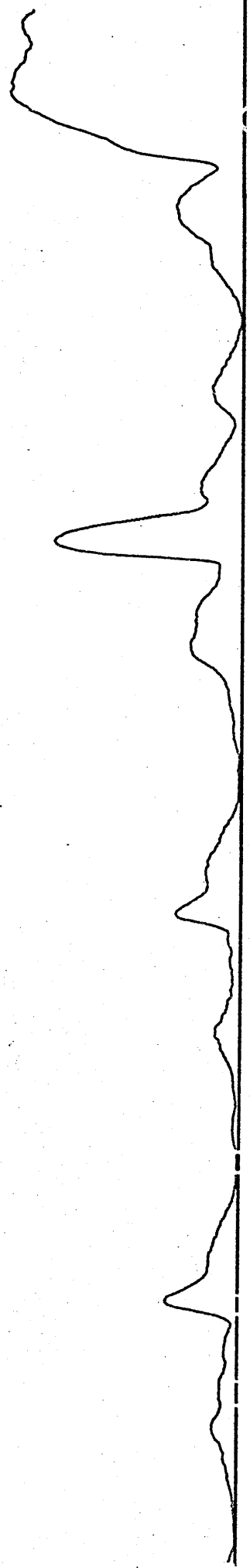
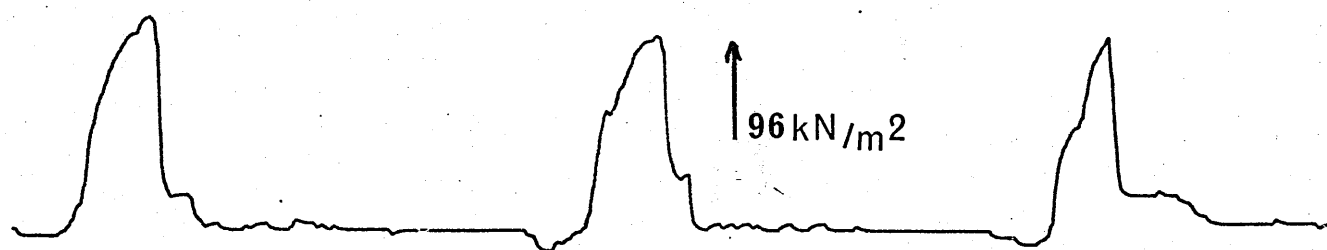


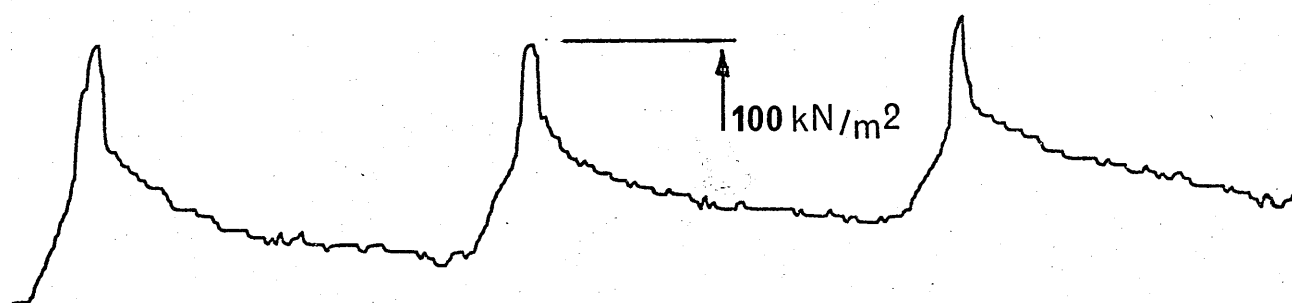
chart from infant generating laryngeal stridor

FIG. 6.4



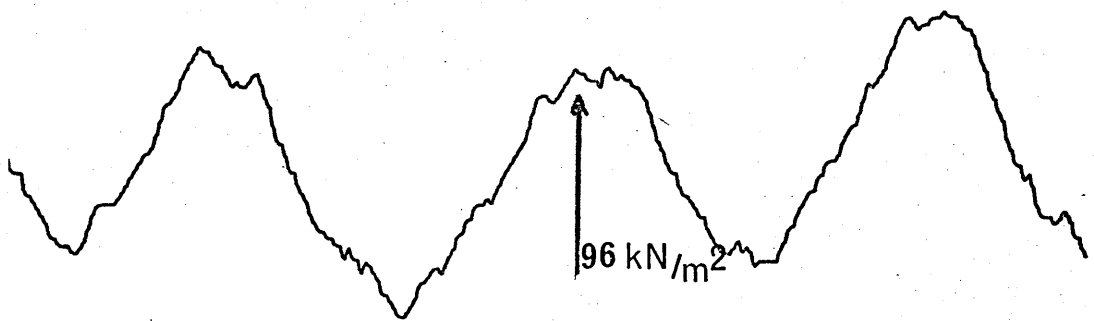
intra-oral pressure without obturator

FIG. 6.5



1st obturator

FIG. 6.6



optimum obturator

FIG. 6.7

from neonates known to be suffering from abnormalities. FIG.6.3 shows the trace produced by an infant with a submucous cleft of the soft palate. From the oral pressure trace it can be seen that the infant was unable to lower the intra-oral pressure and swallowing occurred with difficulty accompanied by some attempt at respiration. FIG.6.4 shows the trace from an infant generating laryngeal stridors. This is a condition often considered to lead to speech defects in later life.

6.04 CLINICAL USE OF THE EQUIPMENT.

Large banks of data are, at the time of writing, being accumulated. It is hoped that a study of this information will reveal recognisable patterns related to palato-glossal malfunction. In the mean time the apparatus has been used clinically to optimise the shape of acrylic feeding plates for infants born with cleft palates. The ability of the infant to produce a lowered intra-oral pressure is dependent on the sealing of this device into the fistula. The traces shown in FIGS. 6.5 to 6.7 reveal the effect of various feeding plates, fitted to the same patient, on the intra-oral pressure produced during suckle. This particular patient had a fistula at the posterior edge of the hard palate and FIG.6.5 shows the sudden rise in the intra-oral pressure as the tongue passes backwards over the fistula allowing air to pass from the nose through the fistula into the mouth.

The effect of altering the shape of the feeding plate can be seen in FIG.6.7 to produce an intra-oral pressure trace approximating the normal.

CHAPTER SEVENDISCUSSION

Both of the equipments described in this thesis were developed because of clinical need and it is the purpose of this chapter to discuss the extent to which the original requirements have been met. Some remarks are made on the limitations of the present equipment, together with suggestions on possible future studies.

During the development of the Nasal Anemometry System it became clear that many other technological aids were needed by speech therapists, but that even the existence of the anemometer enabled them to extend the range of their work. For example most speech therapists only use the airflow readings as a guide to any improvement of nasal escape. Numerical comparisons from recordings taken at intervals of several weeks or months are meaningless unless standardised recording conditions can be established. This is more difficult than might at first be imagined because even normal speakers are unlikely to say the same word in exactly the same way twice. The length and inflection of individual phonemes can vary, sometimes considerably. Some preliminary recordings suggest that using a standard microphone-patient distance and only accepting those recordings which give equal readings on a sound level meter does not result in very repeatable total-airflow volume, or peak-flow, recordings in normal patients, let alone in abnormals. (Variations of about 20% in the peak-flow value during the word "smoke" have been recorded for a normal speaker.) However the incidence of this flow correlated to particular phonemes is consistent from word

to word. Further studies are necessary to see if it is possible to establish a standardised technique, which is not too complex or expensive, before definite improvement in the numerical evaluation of nasal airflow, of a given patient, can be obtained from charts.

Improvements are also needed in the design of the nose-mask. Consideration has to be given to colour, since black is the colour of anaesthetic masks (which these are) and upsets children only too conversant with anaesthetics, and to the smell for similar reasons. In considering size variation and adjustability it is proposed to try to cast masks in silicone rubber or to use a flexible dental-rubber compound. These would be manufactured in three sizes, at least, to accomodate differences of physiognomy.

The use of a thermistor as the airflow transducer seems adequate and the only improvements in the electronics required are to reduce cost and weight. To cheapen the recorder it is proposed to use a multiplexing system and a single track tape-recorder. Cheaper components are also being considered, and a noticable reduction in cost has already been achieved for the V-F converter.

In the case of the feeding monitor, the project is really only in its infancy and has yet to prove its full clinical usefulness. Clinical trials suggest that with care the equipment may be capable of giving useful data on the sucking, swallowing and respiration behaviour of infants but it will be some years before it is known whether anomalies in these patterns are connected with speech defects, or any other neuromuscular

abnormality.

Some technical expertise is required to produce good quality recordings using the equipment in its present form. A standardising and setting-up procedure is required as well as careful monitoring of the equipment during recording. This is not how the project was originally envisaged. It was hoped that the equipment would be useable by intelligent nursing staff and some further thought needs to be given to the design to overcome certain problems. For example, ambient temperature affects the pressure transducer. This can, at present, only be compensated manually at the time of recording. It is our experience that nursing staff do not like having to make this sort of adjustment and electronic compensation to remove this adjustment may be possible. Even so, it may well be that, regretfully, this apparatus may only be of use in a research-based unit with technical aid available.

In developing the equipments described, it has been necessary to co-operate with dental and plastic surgeons, speech therapists and nursing staff. It has also been necessary to work with patients in a clinical situation and to gain their confidence in order to make recordings. Considerable experience has been gained in the techniques of design and construction of apparatus for use by clinicians. For example, the position of knobs and meters, the colour, shape and texture of materials and the general ergonomics of the systems. It is relatively simple for a physicist to construct a perfectly adequate bench-apparatus, but the final assessment of its success is in its acceptability by the clinical profession.

It is considered that this work has, in part, succeeded by producing one equipment, the Nasal Anemometer, now accepted by speech therapists as a useful treatment and assessment aid. It is also hoped that, in time, the feeding monitor will produce useful information on the relationship between infant feeding patterns and speech development, especially with regard to hypernasal speech.

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APPENDIX ONE.

The graph shown is a conversion from kN/m^2 to $\text{cm.H}_2\text{O}$.

